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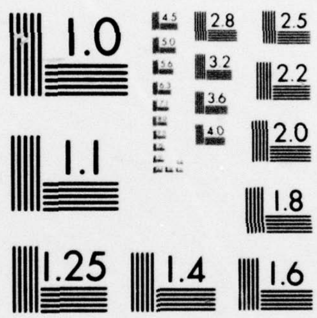

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BALLISTIC BEHAVIOR OF ALUMINUM ALLOY LAMINATES

STUART V. ARNOLD
MATERIALS APPLICATION DIVISION

October 1977

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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ABSTRACT

Fragment penetration of monolithic plate and resin-bonded sheet laminates of aluminum alloy 7475-T371, all of equivalent areal density, is reported as a function of velocity, obliquity, and laminate design. Fragment-simulating projectiles weighing 5.85 and 17.0 grains were used in ballistic tests over ranges of velocity comparable to those attained by actual fragments of 23-mm HEI shell. Findings are discussed with relation to aircraft vulnerability.

CONTENTS

INTRODUCTION

High explosive shell and missile warheads are among the threats which confront Army aircraft. These threats inflict structural damage by combined effects of blast and impact of high velocity fragments. The 23-mm HEI (high-explosive incendiary) shell is particularly deserving of attention. Its mild steel fragments range in weight from less than 0.5 grain to as much as 100 grains. Most fragments occur in the 2.0- to 7.0-grain weight range and attain a total velocity (projectile velocity plus fragmentation velocity) between 4000 and 5500 fps.[1] Heavier fragments, 15 grains in weight, commonly achieve 3000 to 3200 fps velocities.

When a shell fragment strikes aircraft structure, it inflicts primary damage by deforming, rupturing, and/or penetrating the component which it impacts. As a result of such impact, secondary fragments of the impacted material may be ejected from the front surface by cratering action, or from the rear surface by plugging or spalling. The shell fragment itself may completely penetrate the first component and continue to strike another, causing further damage.

The objectives of this investigation were (a) to examine fragment penetration behavior as a function of obliquity and (b) to determine whether lamination of metal structure would serve to enhance protection without increasing weight.

TEST PROCEDURE

An advanced aluminum alloy 7475-T371 was selected as target material to be tested in the form of (1) 0.246-inch-thick plate and (2) laminates approximating this thickness. The 7475 alloy is a high purity variation of alloy 7075 produced by a proprietary process to provide high strength and superior fracture toughness. The chemical composition of this alloy is as follows (in weight percent): 0.10 max. silicon; 0.12 max. iron; 1.2-1.0 copper; 0.06 max. manganese; 1.9-2.6 magnesium; 0.18-0.25 chromium; 5.2-6.2 zinc; 0.6 max. titanium; total others, 0.15; and remainder, aluminum. The T371 treatment is also considered proprietary by the producer.

A number of resin-bonded "solid" laminates and spaced laminates* were designed to approximate closely the areal density of the 0.246-inch plate (3.75 psf). Thus, double laminates were fashioned from 0.125-inch sheet, quadruple laminates from 0.062-inch sheet, and octuple laminates from 0.032-inch sheet. In the foregoing designs 12×12-inch sheets were either bonded face-to-face with AF-126 epoxy resin adhesive or were separated from each other by twice their own thickness using spacers located at the edges. Three other designs incorporated two 0.063-inch and one 0.125-inch sheet spaced 0.125 inch apart.

*These laminates were originally procured as backup materials for composite armor (see AMMRC TR 74-9, "Variables Affecting Performance of Ceramic-Faced Composite Armor (U)," R. Chait and S. J. Acquaviva, April 1974, Confidential Report).

1. ZABEL, P. H. *Fragmentation Data 23mm High-Explosive Incendiary Tracer Projectile (U).* NWC Technical Memorandum 2694, December 1975.

AF-126 is a non-volatile, modified epoxy thermosetting film adhesive designed primarily for structurally bonding metals. Cure can be effected under a pressure of 50 psi and 60 minutes at 250 F or 90 minutes at 225 F.

Tension specimens were machined from longitudinal and transverse coupons cut from the plate and resin-bonded laminates. (Rolling direction was inferred on the basis of surface markings of the plate and of the external laminae of the laminates.) Plates of this alloy 0.246 inch thick were tested to determine their ballistic limits against 5.85- and 17-grain fragment-simulating projectiles (as shown in Figure 1) at 0°, 30°, 45°, and 60° obliquities. Ballistic limits (V_{50}) established in these tests were used as base-line data for comparing behavior of various laminate designs tested with the same fragment-simulating projectiles (FSP) at selected obliquities. Laminates were held with edge clamps during test firing to prevent cumulative separation from shock of successive projectile impacts.

In order to determine the weight of metal lost as result of FSP impact and/or penetration, 0.246-inch-thick test plates were cut into rectangular pieces, each piece containing the crater or hole left by a single FSP. By measuring the piece, calculating the weight on basis of a solid rectangular volume, then subtracting the actual weight of the piece, weight loss was obtained.

DISCUSSION OF TEST RESULTS

Monolithic Plate

Tensile properties of 7475-T371 plate 0.246 inch thick and of double, quadruple, and octuple adhesive-bonded laminates of equivalent areal density are shown in Table 1. Ultimate strength ranged from 68,400 to 76,500 psi; yield strength (0.2% offset) ranged from 61,900 to 69,800 psi; elongation ranged inversely to strength: 17.5 to 13.8 percent. Properties of the plate, double laminate, and quadruple laminate were similar; the octuple laminate was slightly inferior in strength. Directionality of properties was not appreciable. Delamination associated with tensile fracture was minor.

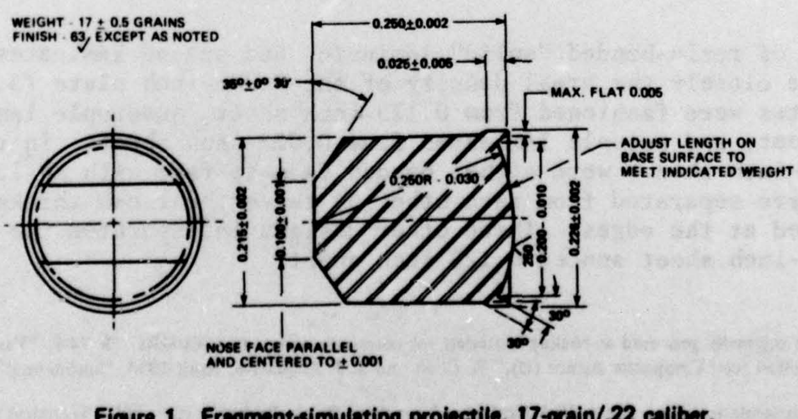


Figure 1. Fragment-simulating projectile, 17-grain/.22 caliber.

Ballistic limits for 7475-T371 plate 0.246 inch thick and corresponding to various test obliquities are shown in Table 2 (see Item 1). These compare favorably with those of 2024-T4 aluminum alloy[2] commonly used in aircraft structures (see Figure 2). (There are relatively few data for ballistic behavior of structural aluminum alloys impacted by small FSPs at velocities equivalent to those of shell fragments.)

Recalling that 2.0- to 7.0-grain fragments from 23-mm HEI shell attain 4000 to 5500 fps velocities and judging by 5.85-grain FSP data, it is indicated that heavier fragments in the 2.0- to 7.0-grain weight range impacting 0.25-inch-thick 7475-T371 aluminum alloy sheet at the lower velocity will completely penetrate at obliquities less than 45°; at the higher velocity, 7.0-grain fragments would penetrate even at 60° obliquity. Also, 17-grain fragments from this shell, commonly possessing velocities in the 3000 to 3200 fps range, will penetrate such 0.25-inch aluminum plate at obliquities less than 60°.

The penetration by 5.85-grain FSPs varies with obliquity and velocity (see Figure 3). When the FSP struck at 0° and velocity near 3000 fps, little cratering of the front face occurred; the FSP pushed out a plug of metal and a circular scab (spall) (see shots 4 and 5, lower right, Figure 3a, and lower left, Figure 3b). When obliquity was increased to 30° and velocity raised to 3600 fps, slight evidence of front face cratering was noted even when the FSP failed to penetrate (see shot 3 near center of Figure 3a). As obliquity is further increased and velocity raised, the cratering loss is greater; thus at 60° obliquity and velocities about 5000 fps the FSP creates a crater larger than itself (see shots 1 and 2, top center, Figure 3a). At these high impact velocities the steel FSP is deformed and eroded.

Similar behavior was observed when 17-grain FSPs impacted the test plate (see Figure 4). It should be recalled that the 17-grain FSPs were fired at velocities ranging from 1700 to 3200 fps, i.e., substantially lower than the 2900 to 5900 fps range of the 5.85-grain FSPs. Fragments of the 23-mm HEI shell weighing roughly 17 grains commonly attain velocities corresponding to the higher end of the 1700 to 3200 fps range.

When weight of metal lost from the plate as result of FSP impact/penetration was plotted against kinetic energy of the FSP, a linear relation for crater loss was indicated. (See Table 3 and lowest curve of Figure 5). Relation of total weight loss on penetration (crater plus punchout plus spall) to kinetic energy was less obvious. Observe that the line for total plate loss from impact and penetration of 17-grain FSPs diverges upward from that for the 5.85-grain FSP as kinetic energy increases. Note also that the 5.85-grain (0.39-grain) FSPs, penetrating obliquely at velocities representative of 23-mm HEI shell fragments of equivalent weight (4000 to 5500 fps), cause plate metal losses weighing 2 to 3 times as much as the FSP itself. This plate metal is, of course, ejected as fragments which have potential for doing secondary damage. The data suggest that roughly 20% of these fragments are ejected from the front face of the plate by cratering action; the remainder eject from the rear face as plugs and spall. The 17-grain (1.10-gram) FSPs penetrating obliquely at representative shell fragment velocities (3000

2. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor - 1976 (U).* Army Materials and Mechanics Research Center, AMMRC TR 76-15, May 1976 (Confidential Report).

Table 1. TENSILE PROPERTIES* OF 7475-T371 ALUMINUM ALLOY PLATE AND ADHESIVE-BONDED LAMINATES OF EQUIVALENT AREAL DENSITY

Specimen		Orientation	Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)	R.A. (%)	Elastic Modulus (ksi)
Plate	1	Longitudinal	67.5	73.5	17.5	38.8	9.9×10^6
	2	"	66.5	72.7	17.2	41.8	10.2
	1	Transverse	65.4	74.0	17.0	38.1	10.1
	2	"	65.7	74.2	17.0	42.7	10.6
Double Laminate	1	Longitudinal	68.4	75.2	16.0	NA	10.4
	2	"	68.2	74.8	15.0		9.9
	1	Transverse	66.7	75.7	14.5		10.2
	2	"	67.2	76.2	16.3		10.4
Quadruple Laminate	1	Longitudinal	69.1	76.5	14.8		10.1
	2	"	69.8	76.5	13.8		10.0
	1	Transverse	67.8	75.9	14.5		10.1
	2	"	67.6	75.6	15.0		9.6
Octuple Laminate	1	Longitudinal	63.4	70.4	14.5		10.2
	2	"	61.9	68.4	15.0		10.1
	1	Transverse	65.0	72.6	15.0		10.8
	2	"	65.8	72.6	15.5		10.5

*Tensile specimens with a reduced section 2.25 × 1.000 × thickness were machined from 12" × 2" blanks. Yield strength was determined at 0.2% offset. Elongation was measured over a gage length of 2.00 inches. Modulus was estimated from the slope of the stress/strain plot. Reduction of area could not be measured on laminated specimens.

Table 2. BALLISTIC LIMITS (V_{50}) FOR 7475-T371 SHEET LAMINATES APPROXIMATING 3.75 PSF AREAL DENSITY IMPACTED BY 5.85- AND 17.0-GRAIN FRAGMENT-SIMULATING PROJECTILES

	Laminate Design						Ballistic Limits/Obliquity				
	Item No.	No. of Lamina	Lamina Thickness (inches)	Lamina Hardness Rockwell B	Lamina Spacing (inches)	Areal Density (psf)	0° (fps)	30° (fps)	45° (fps)	60° (fps)	Remarks
5.85-grain FSP	1	1	0.246	85.6	NA	3.75	2998	3568	4188	5571	
	2	2	0.125	86.7	RB	3.65	3452	-	4099	6150	
	3	4	0.062	90.2	RB	3.65	3377	-	4061	5945	
	4	8	0.031	84.5	RB	3.95	3380	-	4104	5961	
	5	2	0.125	55.8*	0.250		2652	-	3504	5577	Overaged sheet
	6	4	0.062	90.2	0.125		2918	3117	3646	6113†	
	7	8	0.031	84.5	0.062	3.85	2465	-	3147	5433	
	8	3	(0.062-0.062-0.125)		0.125		2743	-	3535	6153	0.062-inch sheet,
	9	3	(0.062-0.125-0.062)		0.125		-	-	-	5562	90.2 RG; 0.125
	10	3	(0.125-0.062-0.062)		0.125		-	-	-	6193	inch, 55.8 RG*
17.0-grain FSP	11	1	0.246	85.6	NA	3.75	1631	-	2391	3158	
	12	2	0.125	86.7	RB	3.65	1990	-	2640	3927	
	13	4	0.062	90.2	RB	3.65	1940	-	2759	3715	
	14	8	0.031	81.5	RB	3.95	2158	-	2723	4296	
	15	2	0.125	55.8	0.250		1806	-	-	3349	Overaged sheet
	16	4	0.062	90.2	0.125		1906	-	-	2969	

NA - not applicable
RB - resin bonded, minimal spacing
*The 0.125-inch-thick sheet used in spaced laminates was obtained by thermally separating resin-bonded double laminates previously prepared. This procedure overaged the sheet and reduced its hardness.
†At 60° the 6113 fps value represents partial penetration at the maximum powder charge.

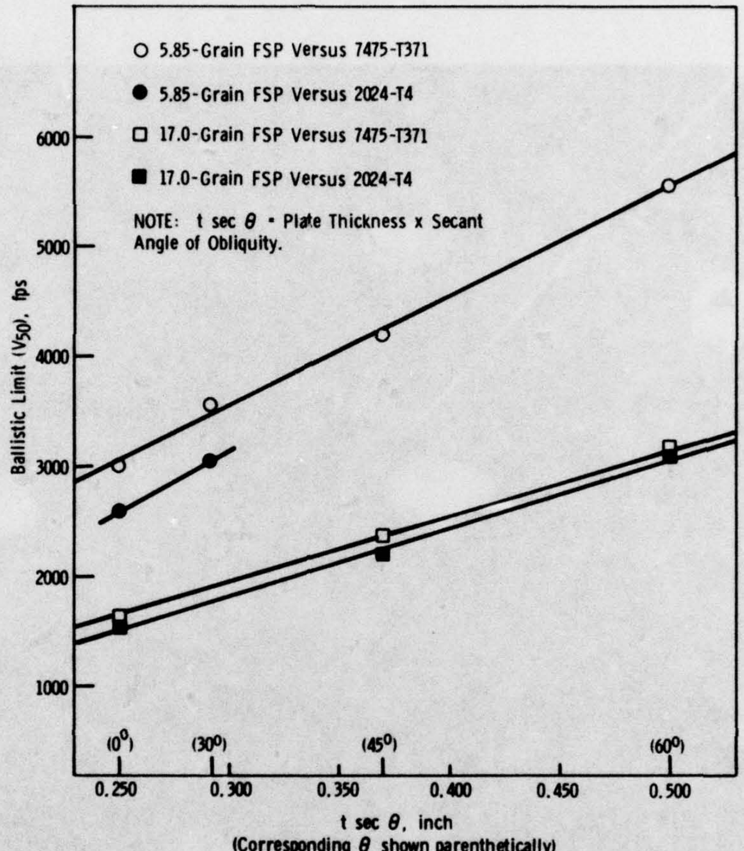


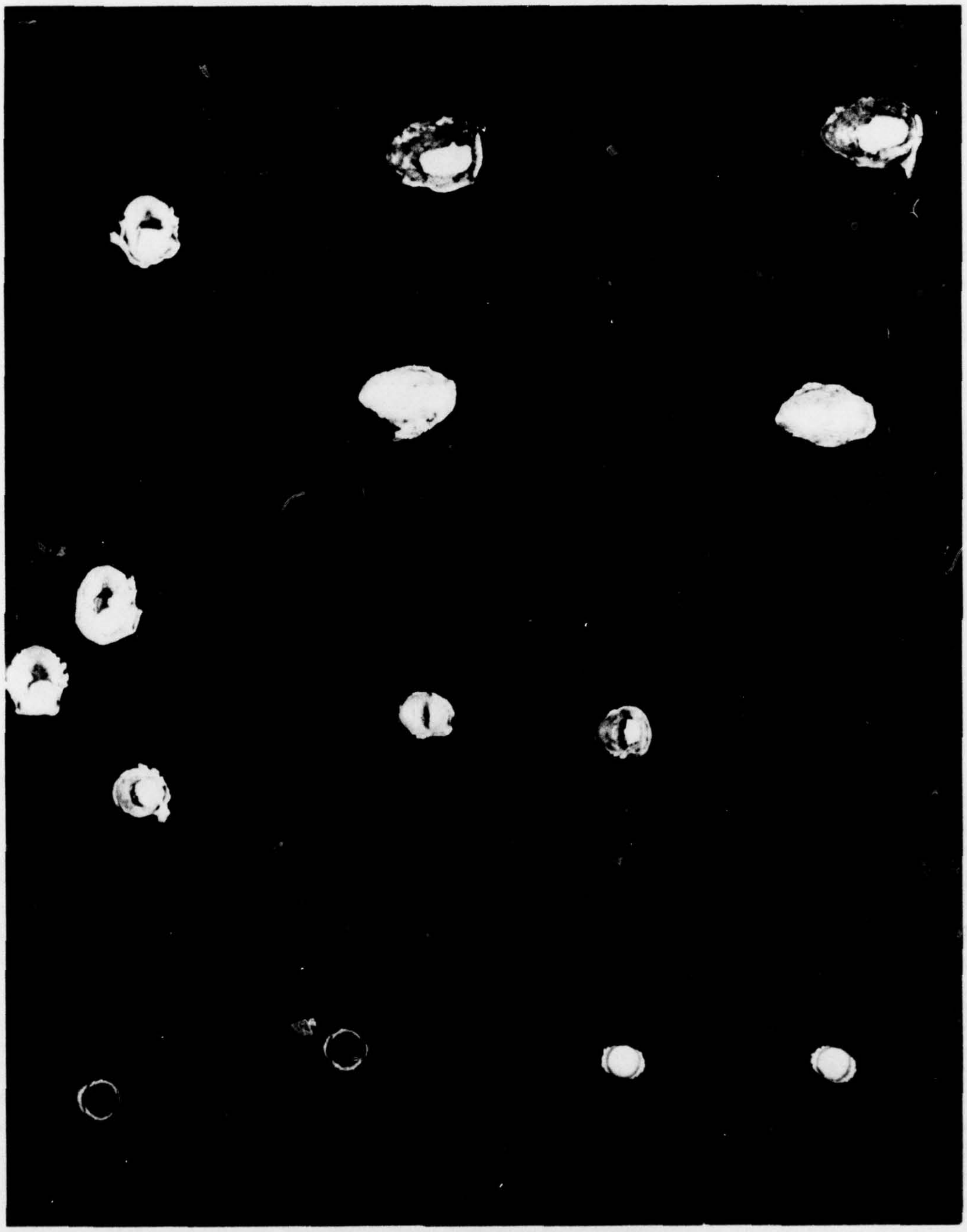
Figure 2. Ballistic limits (V_{50}) of 0.25-inch 2024-T4 and 7475-T371 aluminum alloy plate versus 5.85- and 17-grain fragment-simulating projectiles at various obliquities.

to 3200 fps) cause plate loss about 1.3 times their own weight. Roughly a fourth of this loss was ejected as fragments from the front of the plate. Of course, shell fragments which fail to penetrate when striking obliquely may (1) ricochet and (2) cause cratering loss from the front of the plate. Ricocheted shell fragments and ejected plate fragments from cratering possess potential for inflicting secondary damage to personnel and software.

Resin-Bonded Laminates

The mechanical behavior of laminates has been the subject of considerable research. Resistance to crack propagation in the short transverse direction is greatly increased by lamination.[3] Also, the resistance of some metals to tearing in the plane of the sheet (or laminate) undergoes a transitional increase as sheet (lamina) thickness decreases[3,4] (although in aluminum and its alloys such a transition does not occur[5]). Whereas the above aspects of laminate behavior are purely

3. ARNOLD, S. V. *Toughness of Steel Sheet: The Advantage of Laminating.* Army Materials and Mechanics Research Center, WAL TR 834.21/2, October 1960.
4. ARNOLD, S. V. *Notch Sensitivity and Resistance to Tearing of Titanium Alloy Sheet.* Army Materials and Mechanics Research Center, WAL TR 405.2/3, April 1959.
5. ARNOLD, S. V. *Notch Sensitivity and Laminated Charpy Impact Strength of 1100-F and 2024-T4 Aluminum Alloy Simulated Sheet.* Army Materials and Mechanics Research Center, WAL TR 341.5/1, September 1959.



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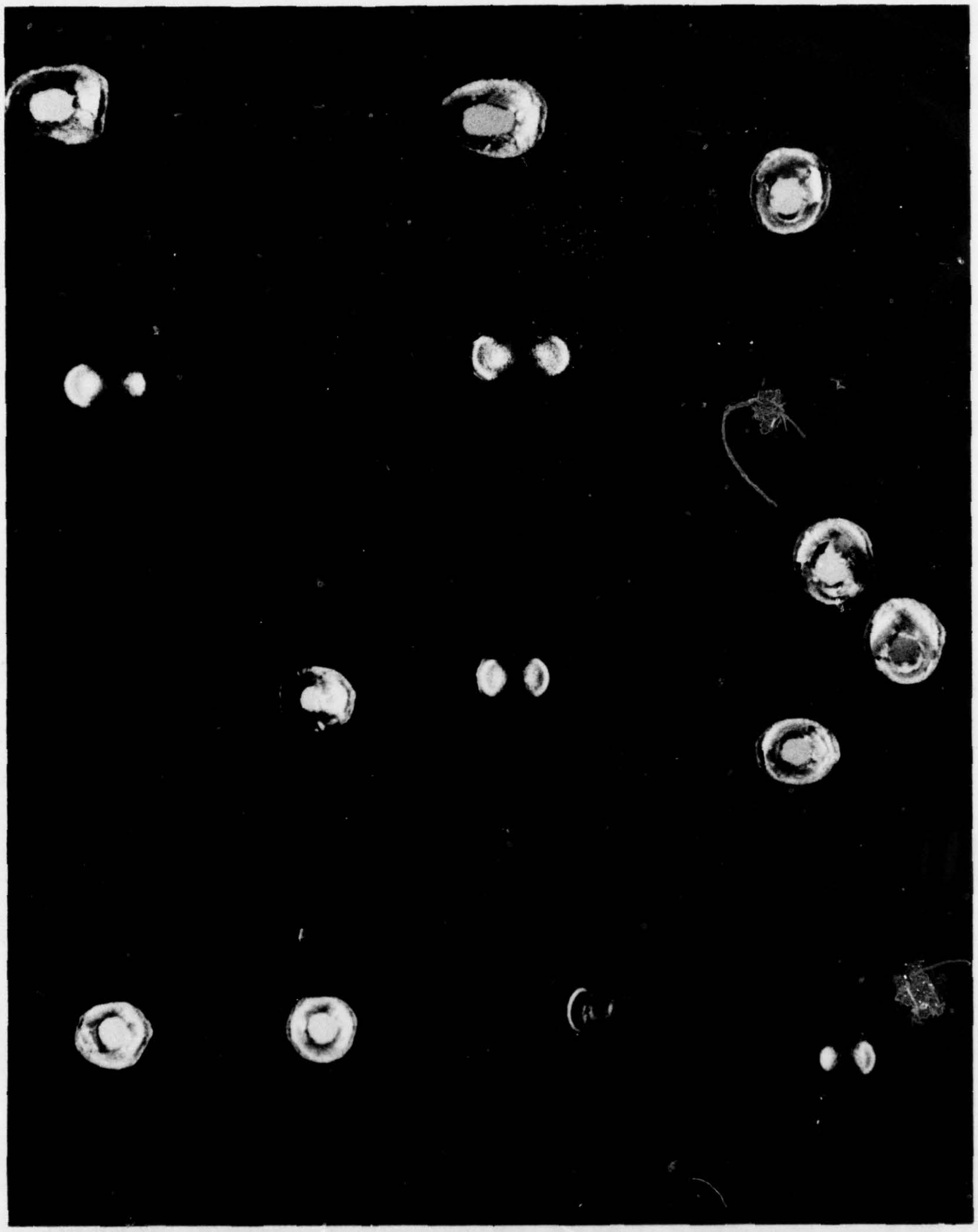

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Figure 3. Front (a) and rear (b) faces of 0.25-inch 7475-T371 plate used to establish V_{50} for the 5.85-grain fragment-simulating projectile at 0°, 30°, 45°, and 60° obliquities.

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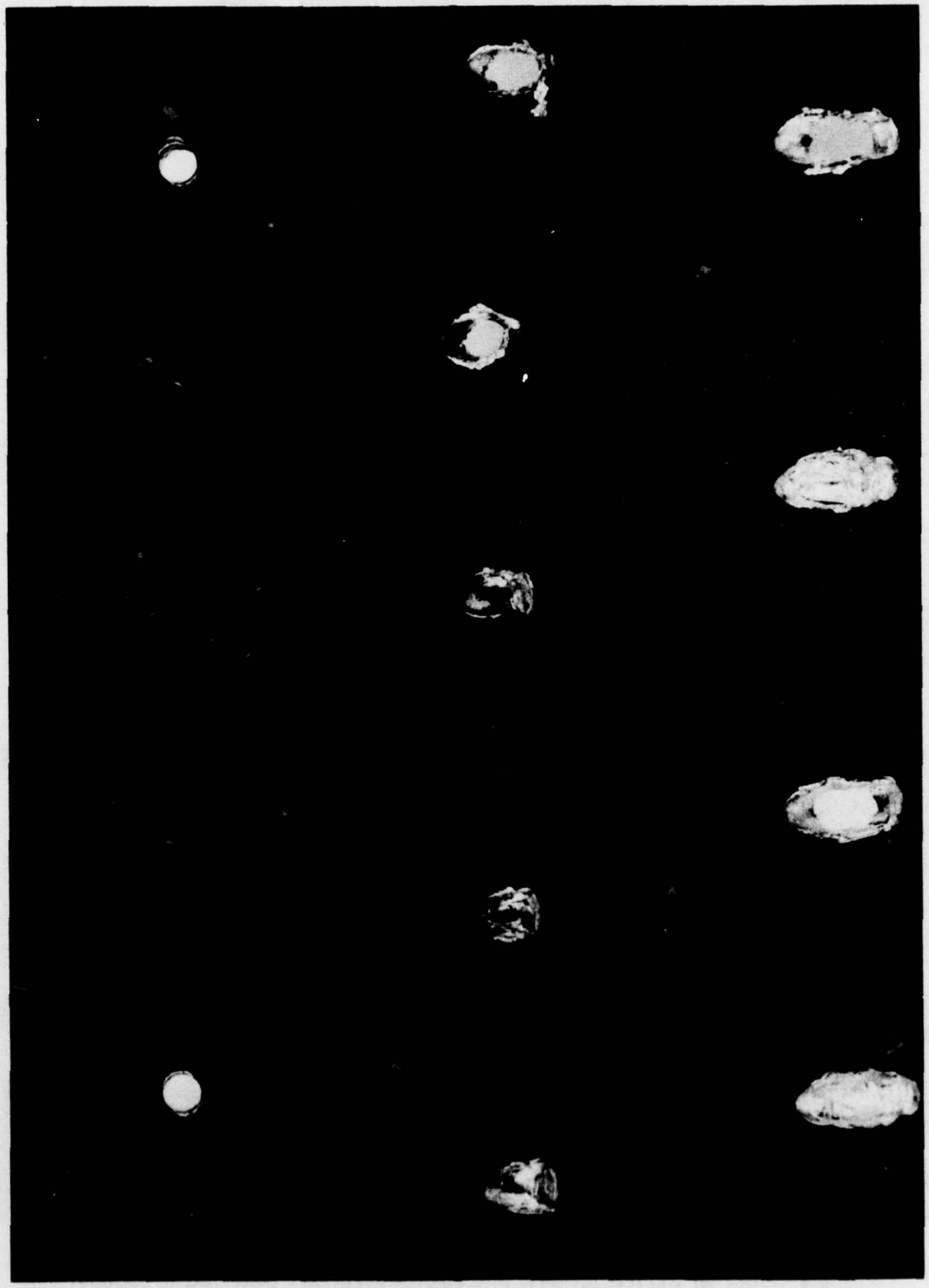

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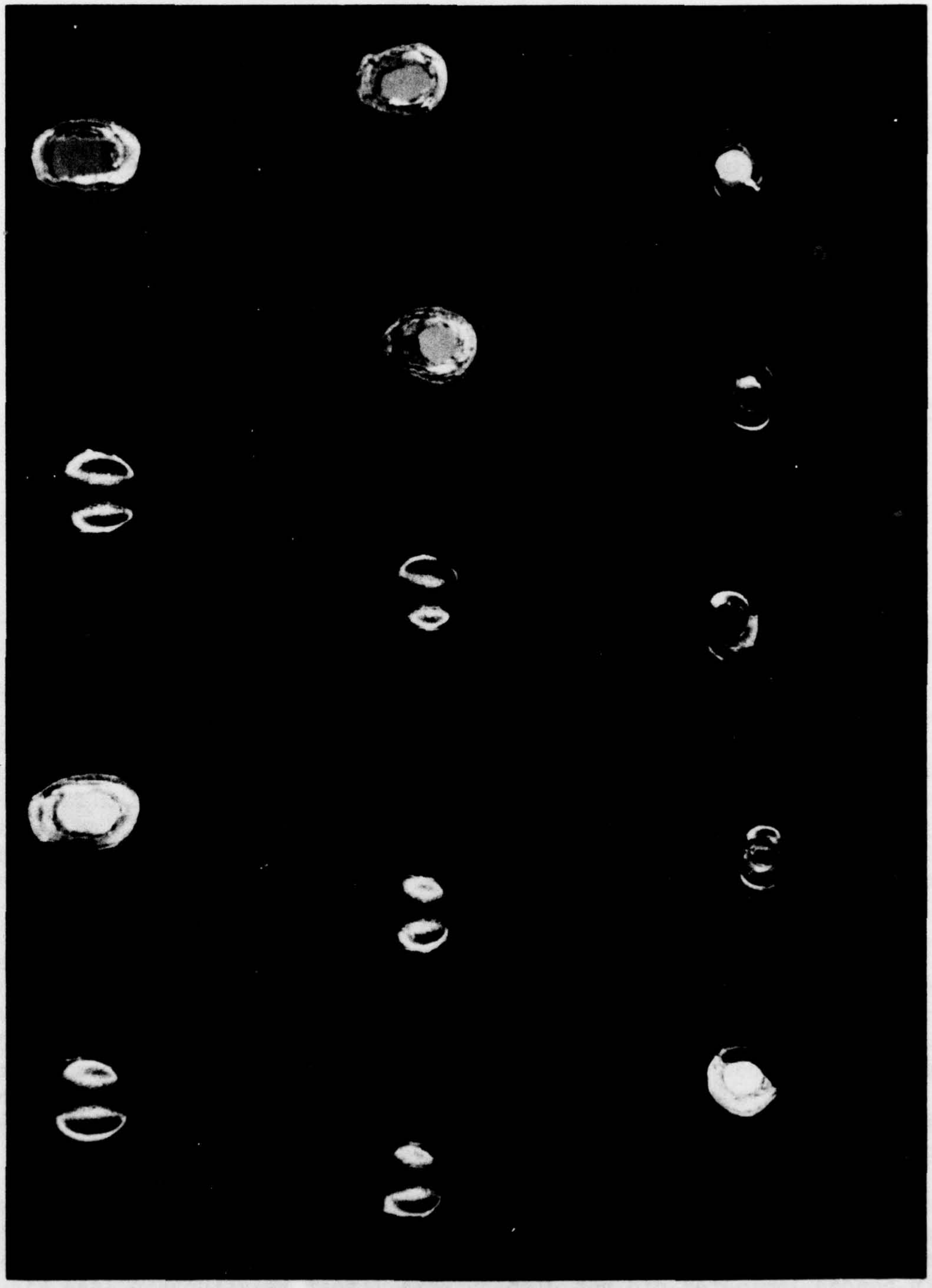

(b)

Figure 4. Front (a) and rear (b) faces of 0.25-inch plate of 7475-T371 used to establish V_{50} for the 17-grain fragment-simulating projectile at 0°, 45°, and 60° obliquities.

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Table 3. PLATE METAL* LOSS FROM FSP IMPACT/PENETRATION

	Specimen No.	Velocity (fps)	Kinetic Energy (ft-lb)	Obliquity (degrees)	Loss (grams)	Comment
5.85-grain FSP data	504	2952	113.6	0	0.50	Complete penetration with spall.
	505	3043	120.3	0	0.63	Complete penetration with spall.
	532	3400	150.2	30	0.48	Partial penetration with spall.
	533	3509	160.0	30	0.08	Partial penetration with no spall.
	534	3722	180.0	30	1.42	Complete penetration with spall.
	535	3625	170.8	30	1.40	Complete penetration with spall.
	541	4462	258.8	45	0.93	Complete penetration with spall.
	542	4344	245.3	45	0.81	Complete penetration with spall.
	545	4074	215.7	45	0.16	Partial penetration with no spall.
	546	4126	221.2	45	0.64	Complete penetration with spall.
	547	4250	234.8	45	0.66	Complete penetration with spall.
	561	4696	286.6	60	0.19	Partial penetration with no spall.
	563	5835	442.5	60	1.19	Complete penetration with spall.
	565	5630	411.9	60	1.17	Complete penetration with spall.
17.0-grain FSP data	1701	1746	115.0	0	0.46	Complete penetration with no spall.
	1702	1680	106.5	0	0.52	Complete penetration with partial spall.
	1741	2550	245.3	45	1.23	Complete penetration with spall.
	1742	2250	191.0	45	0.13	Partial penetration with no spall.
	1743	2234	188.3	45	0.10	Partial penetration with no spall.
	1745	2379	213.5	45	1.36	Complete penetration with spall.
	1746	2402	217.7	45	1.04	Complete penetration with spall.
	1761	3002	340.0	60	1.49	Complete penetration with spall.
	1762	3083	358.6	60	0.40	Partial penetration with no spall.
	1763	3213	389.5	60	1.49	Complete penetration with spall.
	1764	3103	363.3	60	0.41	Partial penetration with no spall.

*Aluminum alloy 7475-T371 plate 0.246 inch in thickness.

mechanical in nature, it often happens that improved metallurgical properties are realized as thickness of the rolled product decreases. Thus a laminate may also reflect improvements attributable to better metallurgical properties in the sheet from which it is assembled. However, laminates used in the subject investigation were fashioned from sheet the properties of which were reasonably similar (see Table 1). Since ballistic behavior of aluminum alloys is not sensitive to minor variations in hardness, or to compositional differences within commercial tolerance, these 7475-T371 sheet were assumed metallurgically identical for purposes of this research.

To facilitate comparison, "solid" resin-bonded laminates incorporating several different numbers of laminae were designed to approximate the same areal density: a "single lamina" of sheet 0.246 inch thick, actual weight 3.75 psf; a double laminate of sheet 0.125 inch thick, actual weight 3.65 psf; a quadruple laminate of sheet 0.062 inch thick, actual weight 3.65 psf; and an octuple laminate of sheet 0.031 inch thick, actual weight 3.95 psf. Actual weights of the latter three laminates include some resin adhesive; the amount (not measured) presumably increased with the number of laminae.

Tests with 5.85-grain and 17.0-grain FSPs showed that ballistic limits for the single lamina (0.246 inch sheet) varied linearly with t sec θ where θ, the angle of obliquity, was variously 0°, 30°, 45°, and 60°; ballistic limits (BL) for resin-bonded laminates did not display this linear relationship (see Figure 6). Ballistic limits are listed in Table 2.

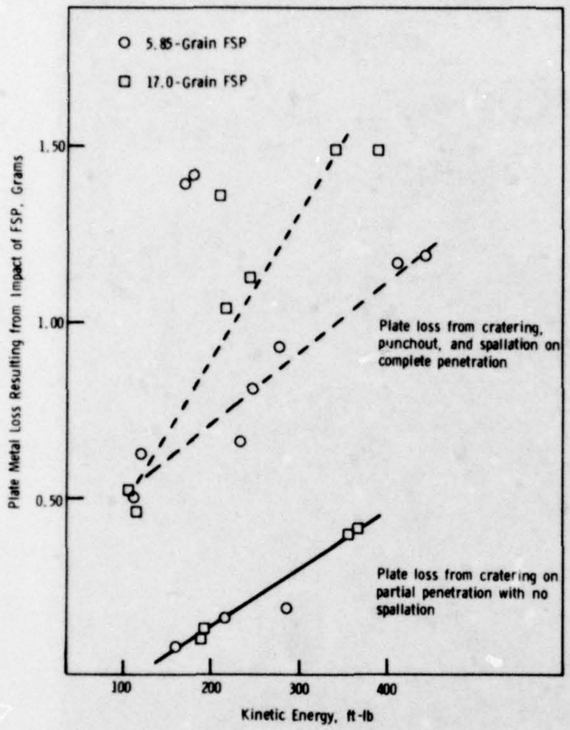


Figure 5. Plate metal loss from impact of penetration by fragment-simulating projectiles.

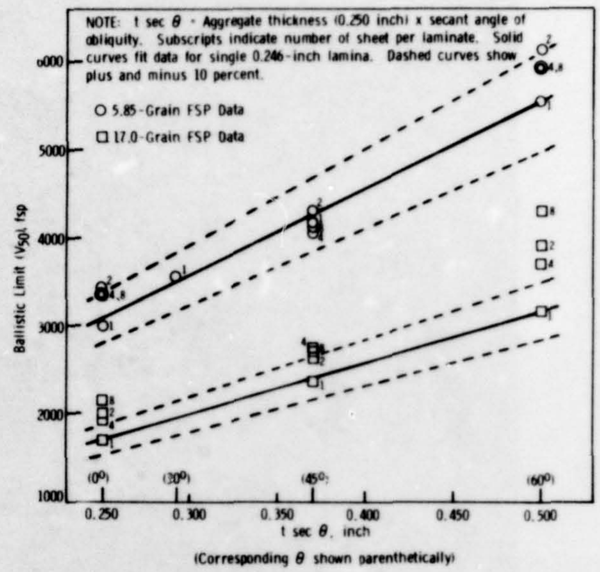
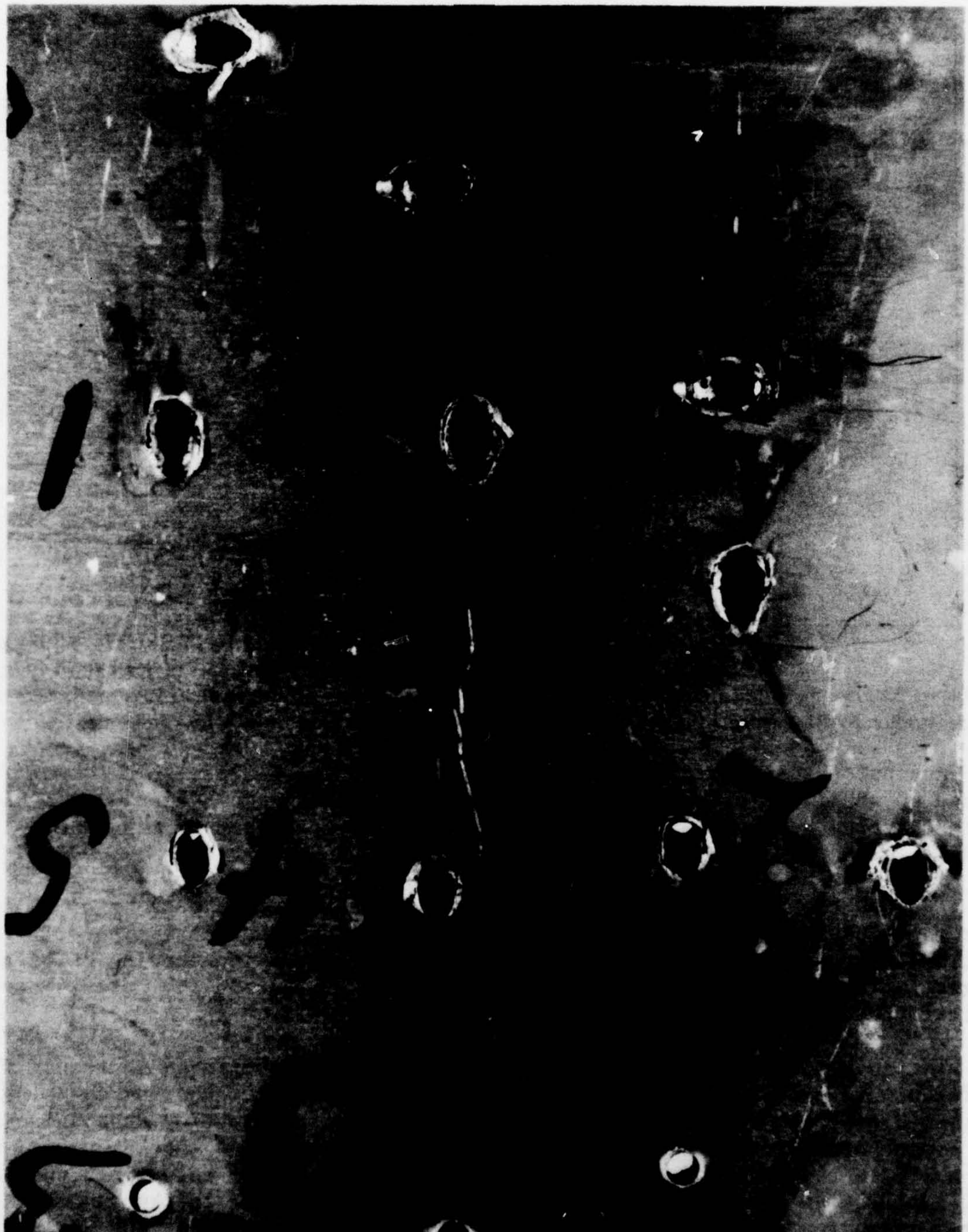


Figure 6. Ballistic limits (V_{50}) of 7475-T371 plate and resin-bonded laminates of approximately 3.75 psf areal density at various obliquities versus 5.85- and 17-grain fragment-simulating projectiles.

Against the 5.85-grain FSP, lamination served to increase BL by about 10% at 0° and 60° obliquities, but made little difference at 45°. Against the 5.85-grain FSP, the double laminate was somewhat more effective than the quadruple and octuple laminates which latter performed similarly.

Against the 17.0-grain FSP, lamination served to increase BL by at least 10% over those of the single lamina at 0°, 45°, and 60° obliquities. The octuple "solid" laminate was particularly effective at 0° and 60°, exceeding BL of the single lamina by about 25% and 35%, respectively. All solid laminates showed minimal (10% to 15%) improvements in BL at 45° obliquity.

The superior ballistic performance of laminates is believed to result from a difference in material response to projectile penetration. Whereas the single lamina (0.246-inch sheet) showed evidence of front-face ejection under high velocity impact plus plug formation and back-spall on penetration (see Figures 3 and 4), the multiple resin-bonded laminates showed less evidence of face ejection and back-spalling as the number of laminae increased and lamina thickness decreased correspondingly (see Figures 7-12). However, FSP penetration of the laminates resulted in extensive local deformation and tearing of the individual laminae. Whereas some portions of petals on the front face tore off, those on the rear face usually remained attached for impact velocities at or below the ballistic limit. Petal formation increased with the number of laminae: it was lacking in single and double laminates, present to a limited extent in the quadruple laminate,



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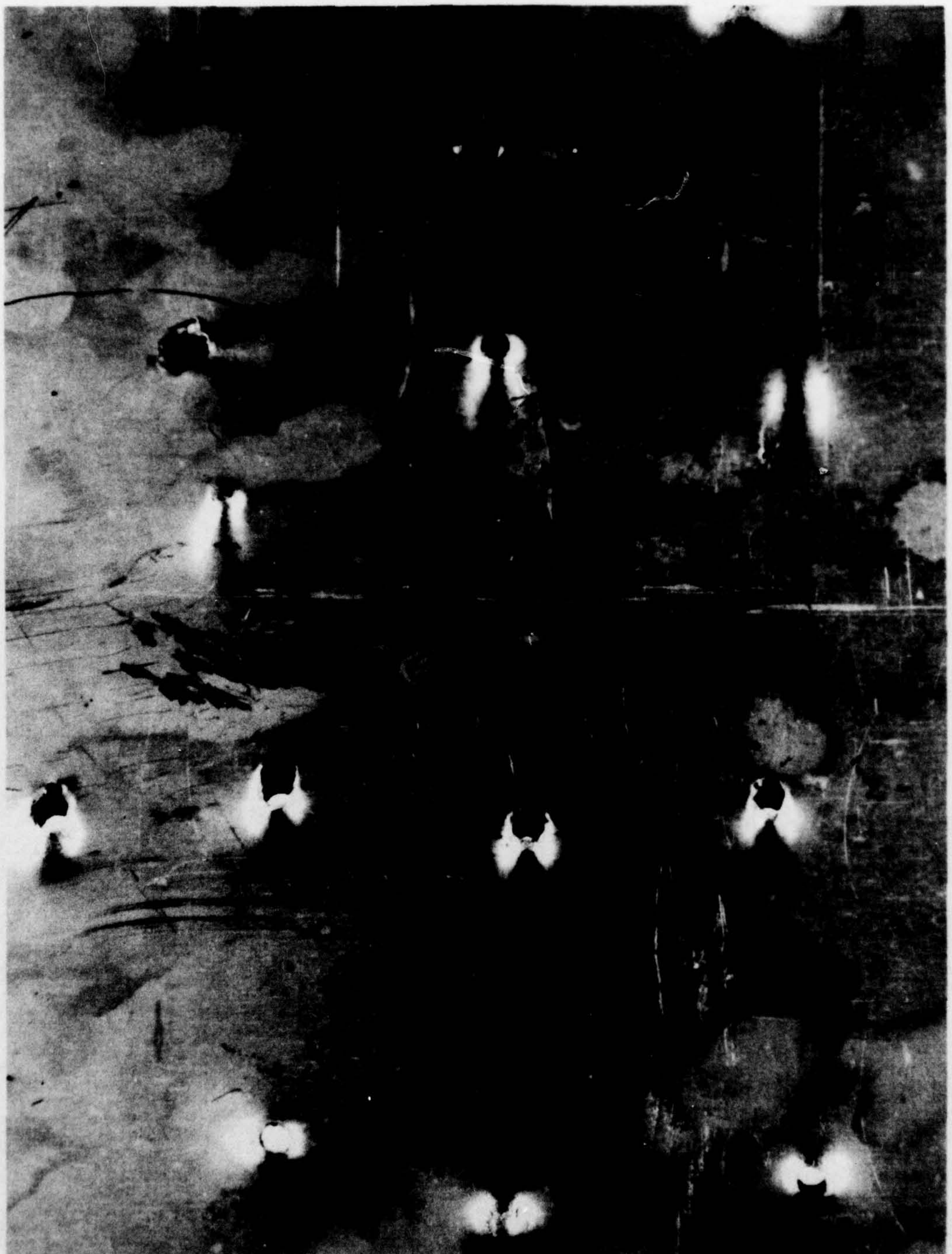

(b)

Figure 7. Front (a) and rear (b) faces of 0.25-inch resin-bonded double laminate of 7475-T371 0.125-inch sheet used to establish V_{50} for the 5.85-grain fragment-simulating projectile at 0°, 45°, and 60° obliquities.

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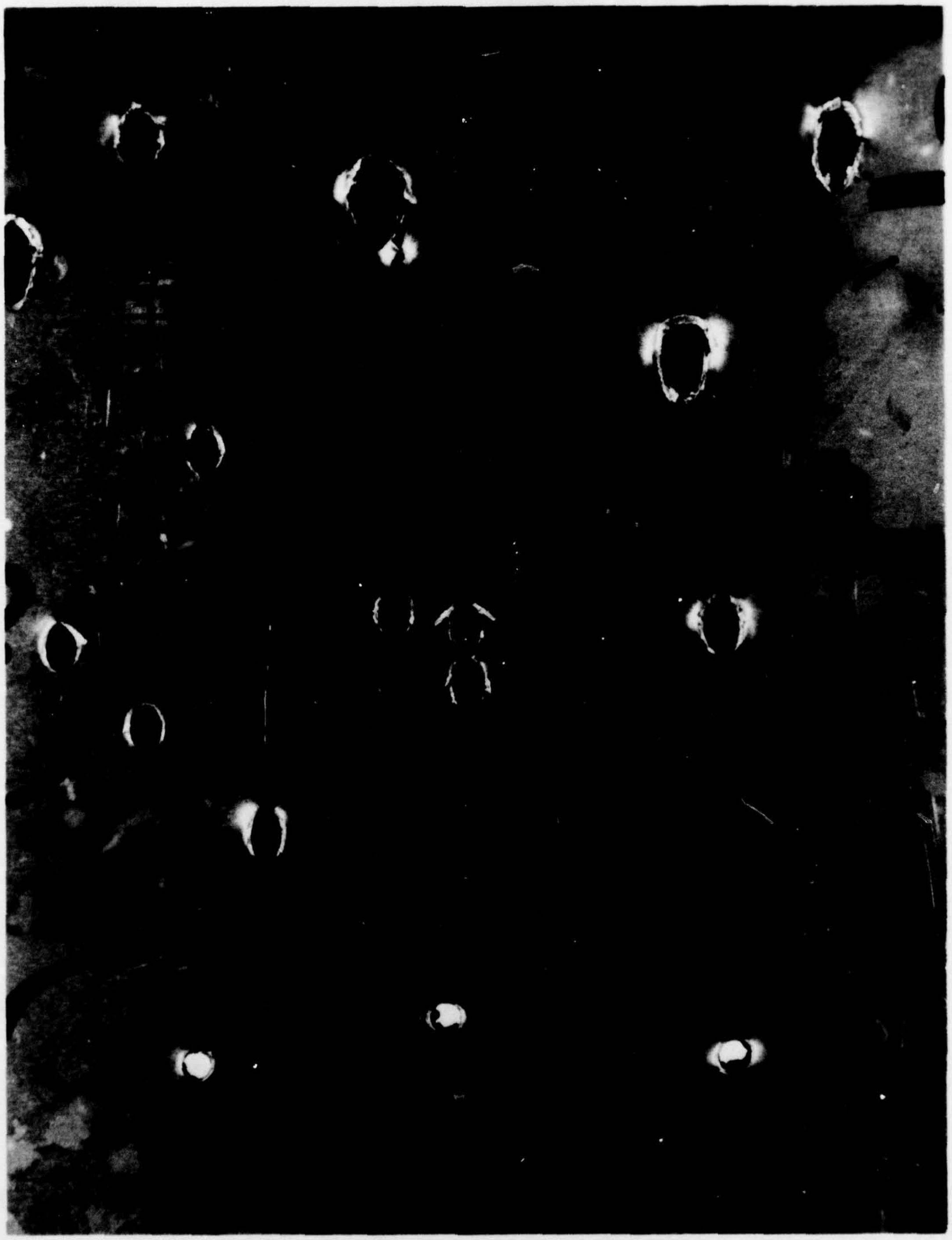

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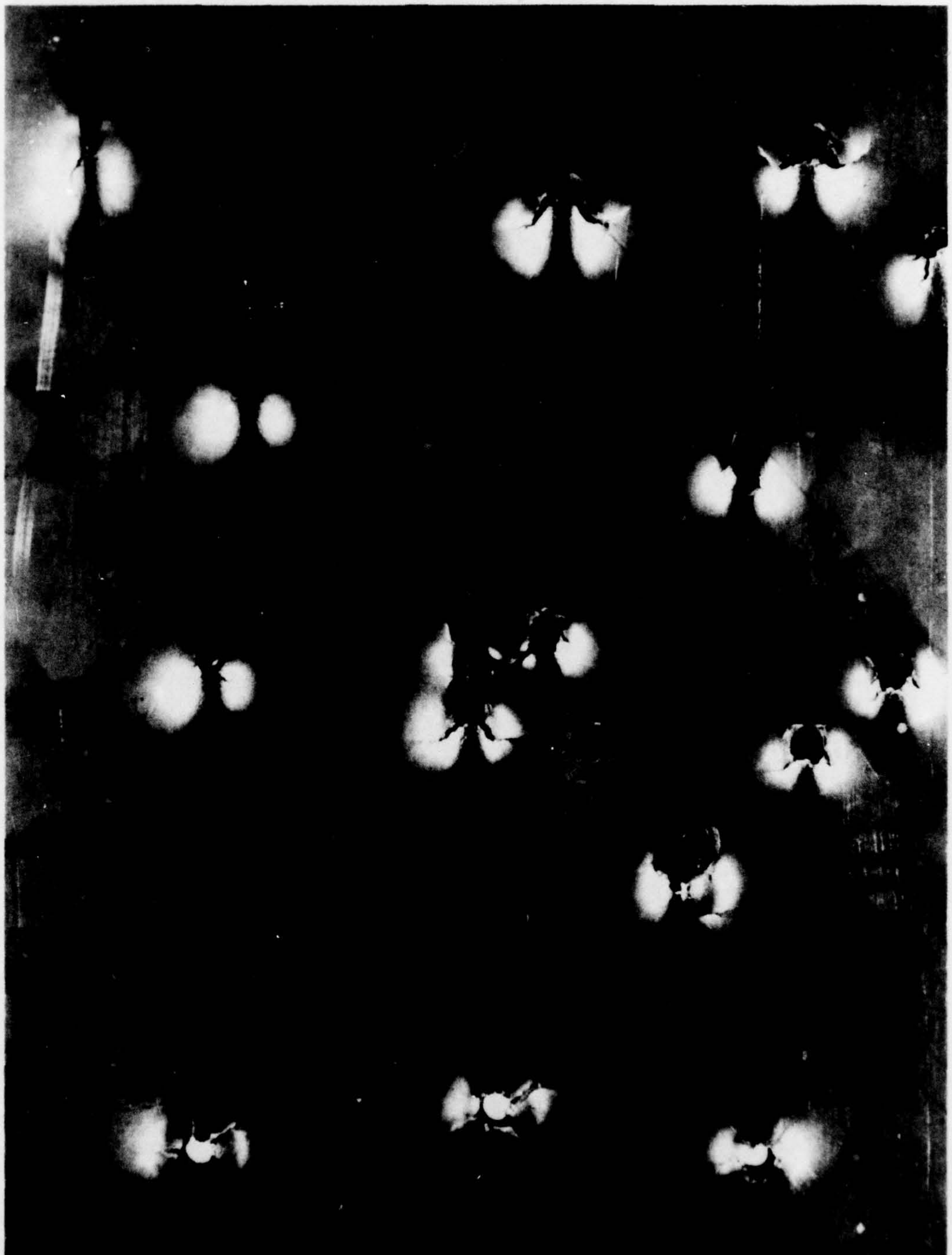

(b)

Figure 8. Front (a) and rear (b) faces of 0.25-inch resin-bonded quadruple laminate of 7475-T371 0.062-inch sheet used to establish V_{50} for the 5.85-grain fragment-simulating projectile at 0°, 45°, and 60° obliquities.

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(a)

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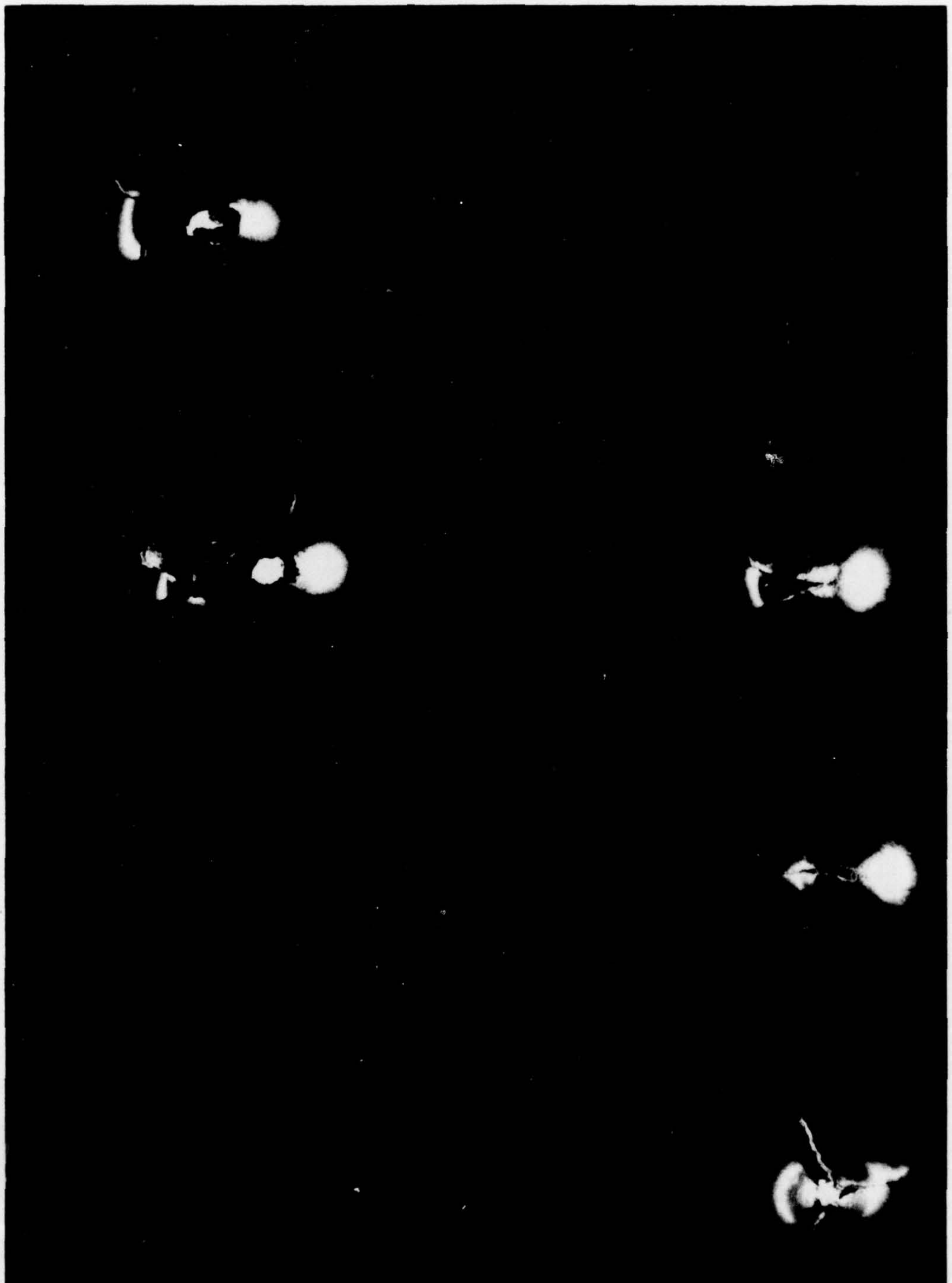

(b)

Figure 9. Front (a) and rear (b) faces of 0.25-inch resin-bonded octuple laminate of 7475-T371 0.032-inch sheet used to establish V_{50} for the 5.85-grain fragment-simulating projectile at 0°, 45°, and 60° obliquities.

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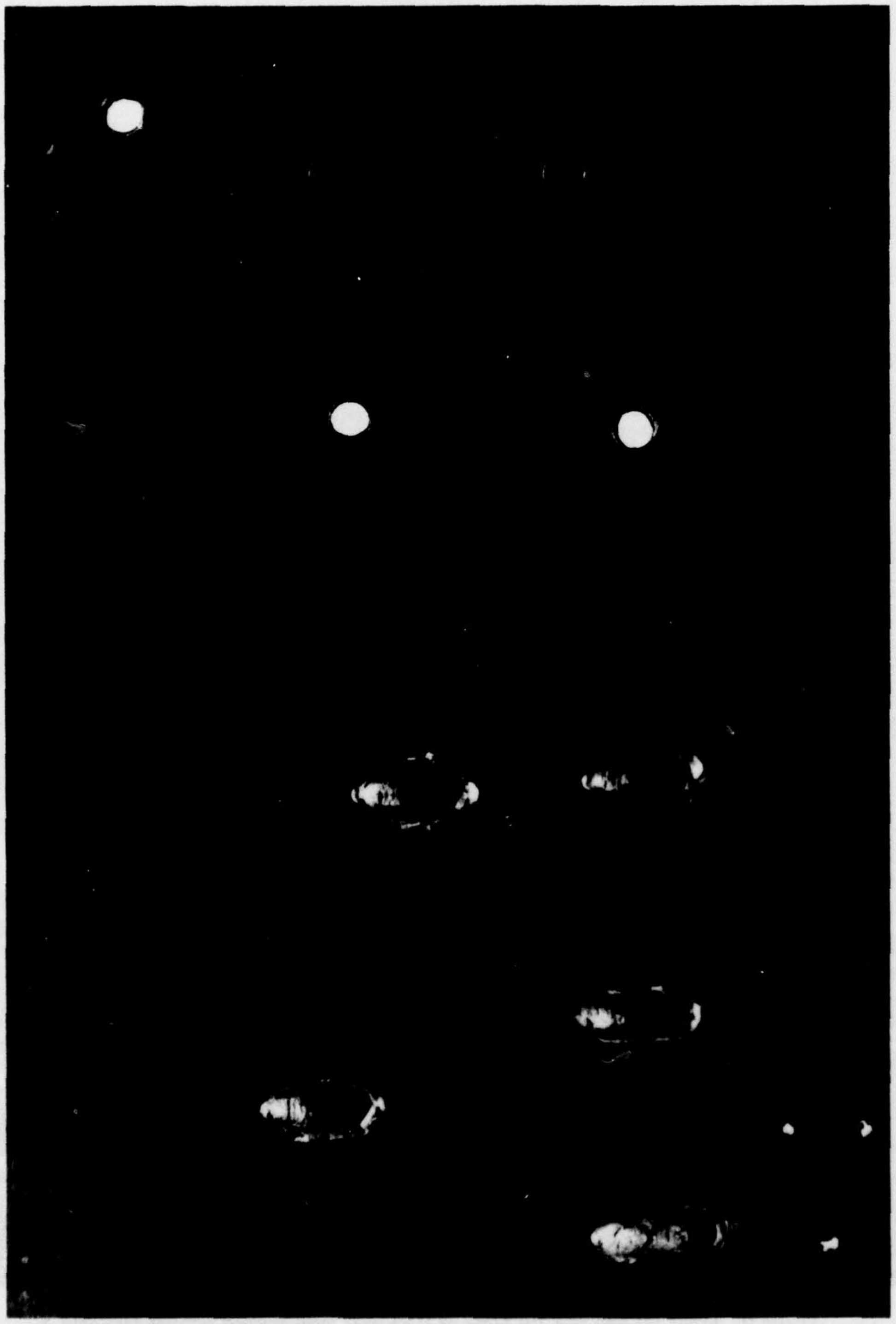

(a)

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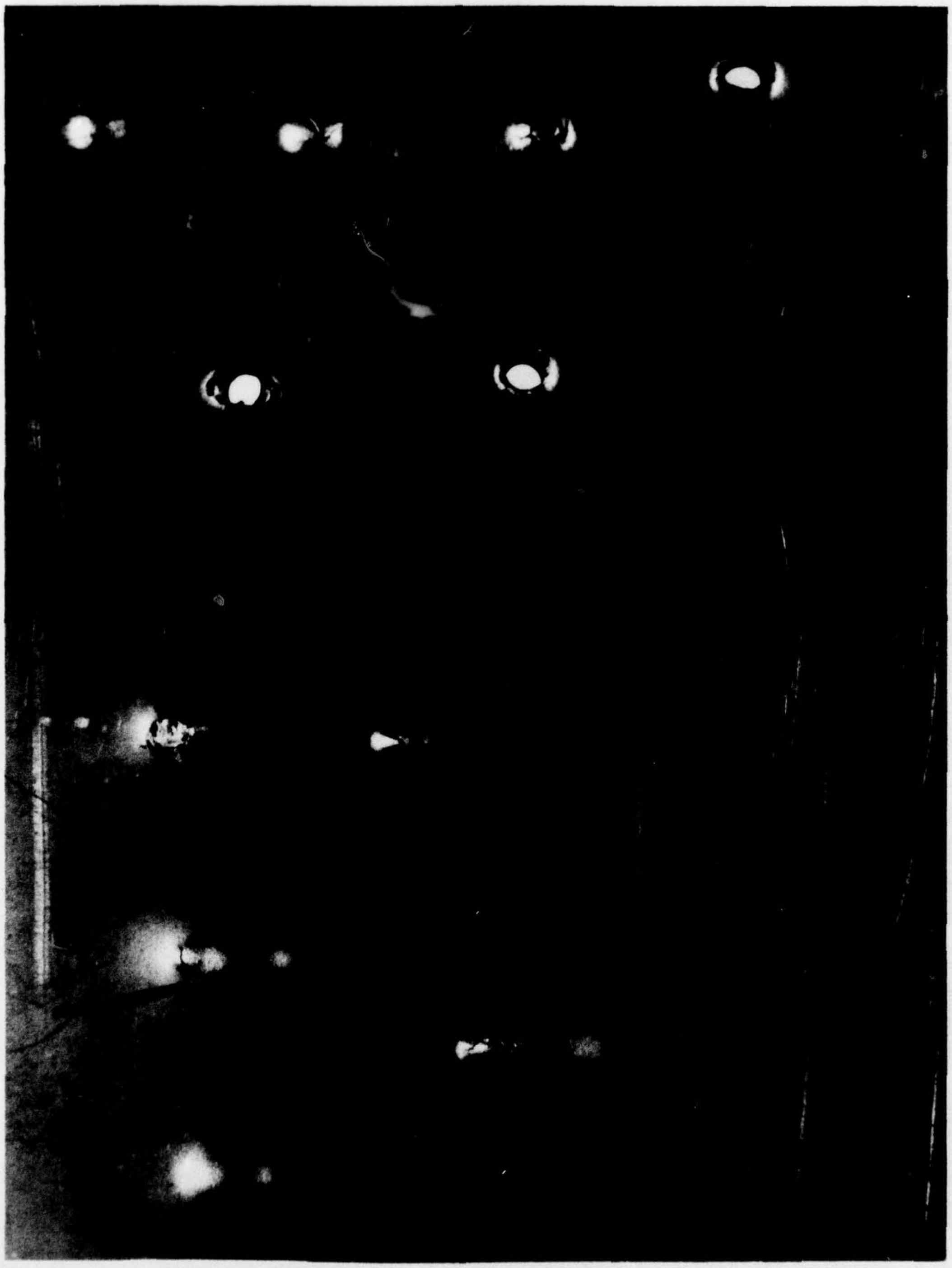

(b)

Figure 10. Front (a) and rear (b) faces of 0.25-inch resin-bonded double laminates of 7475-T371 0.125-inch sheet used to establish V_{50} for the 17.0-grain fragment-simulating projectile at 0° and 60° obliquities.

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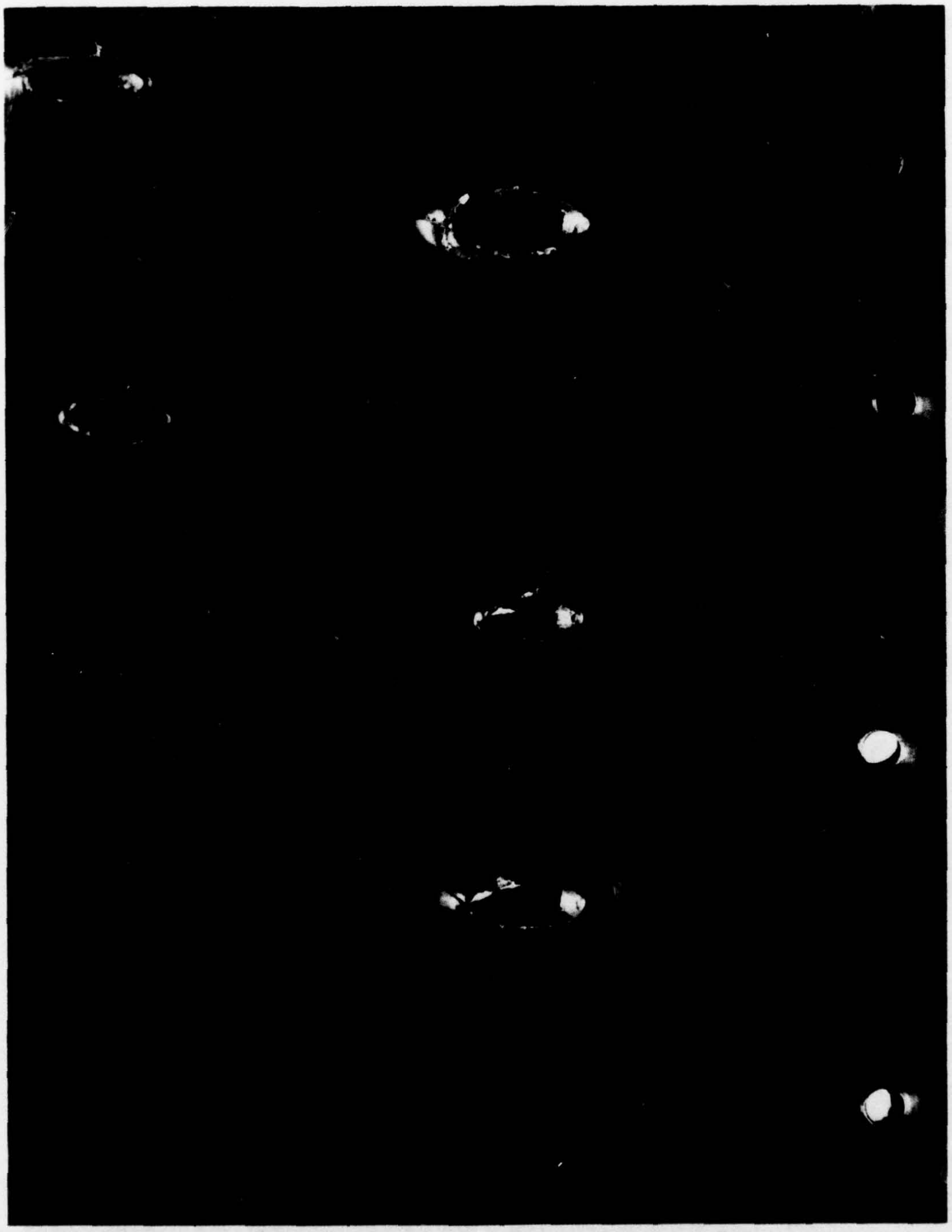

(a)

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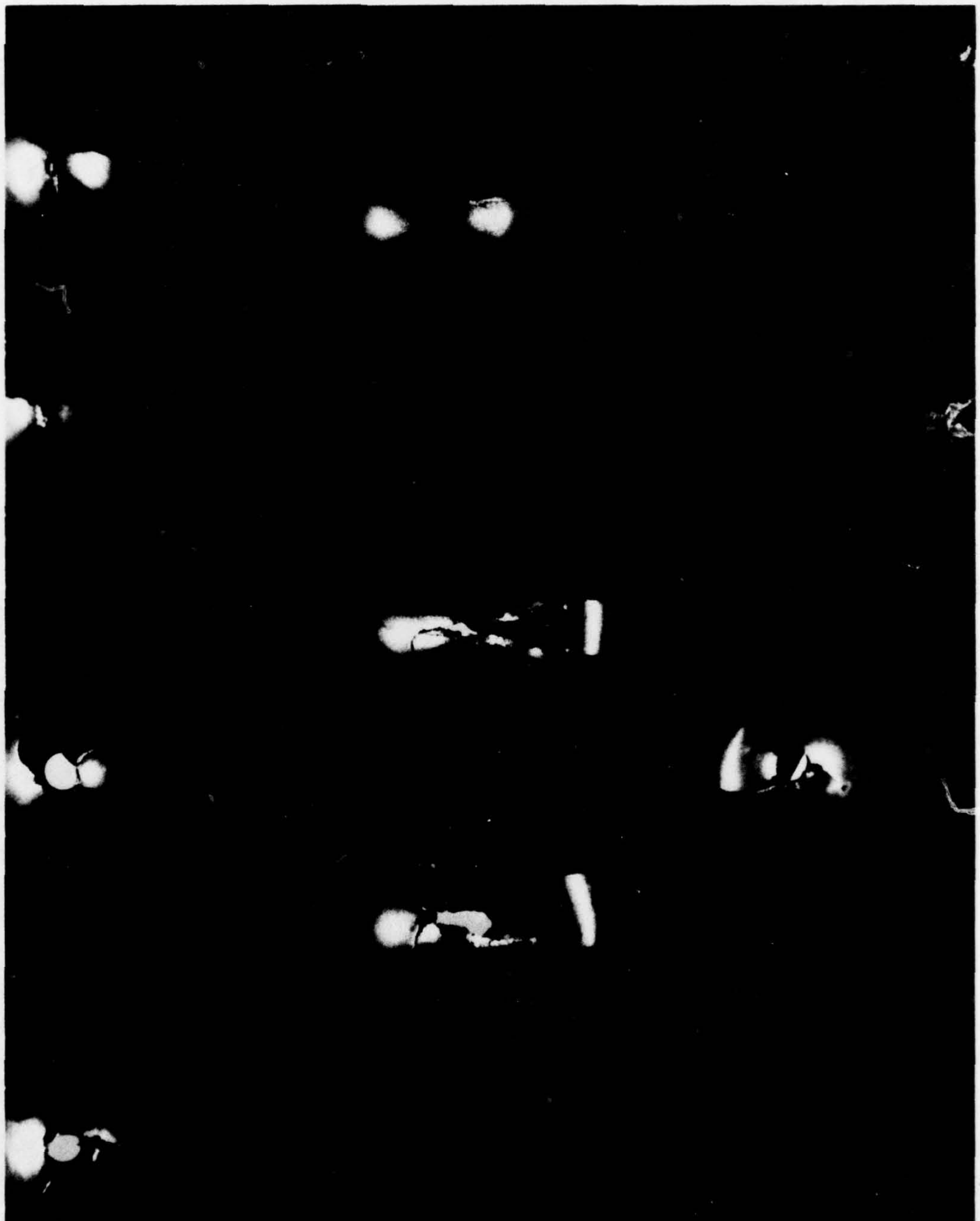

(b)

Figure 11. Front (a) and rear (b) faces of 0.25-inch resin-bonded quadruple laminate of 7475-T371 0.062-inch sheet used to establish V_{50} for the 17.0-grain fragment-simulating projectile at 0° and 60° obliquities.

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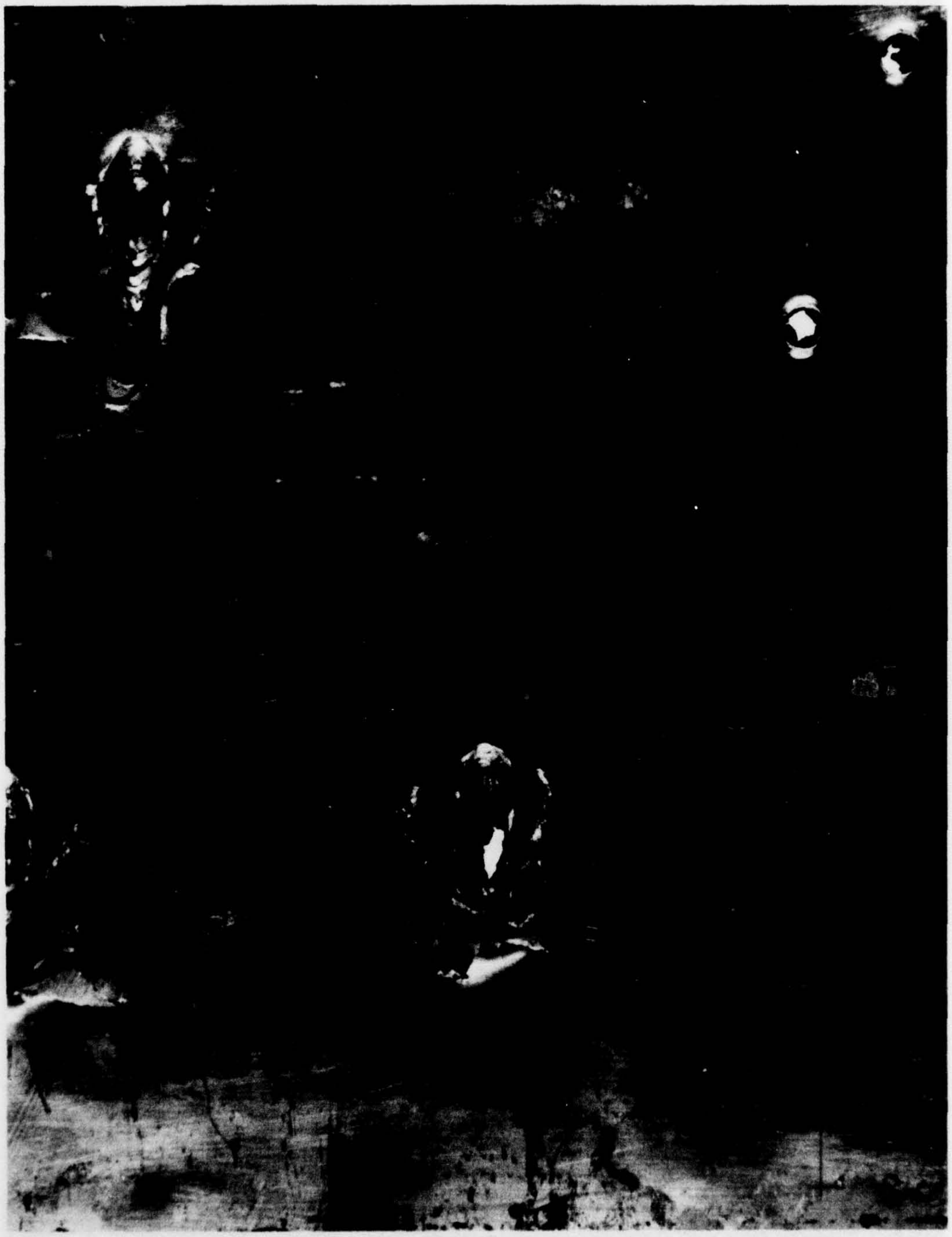

(a)

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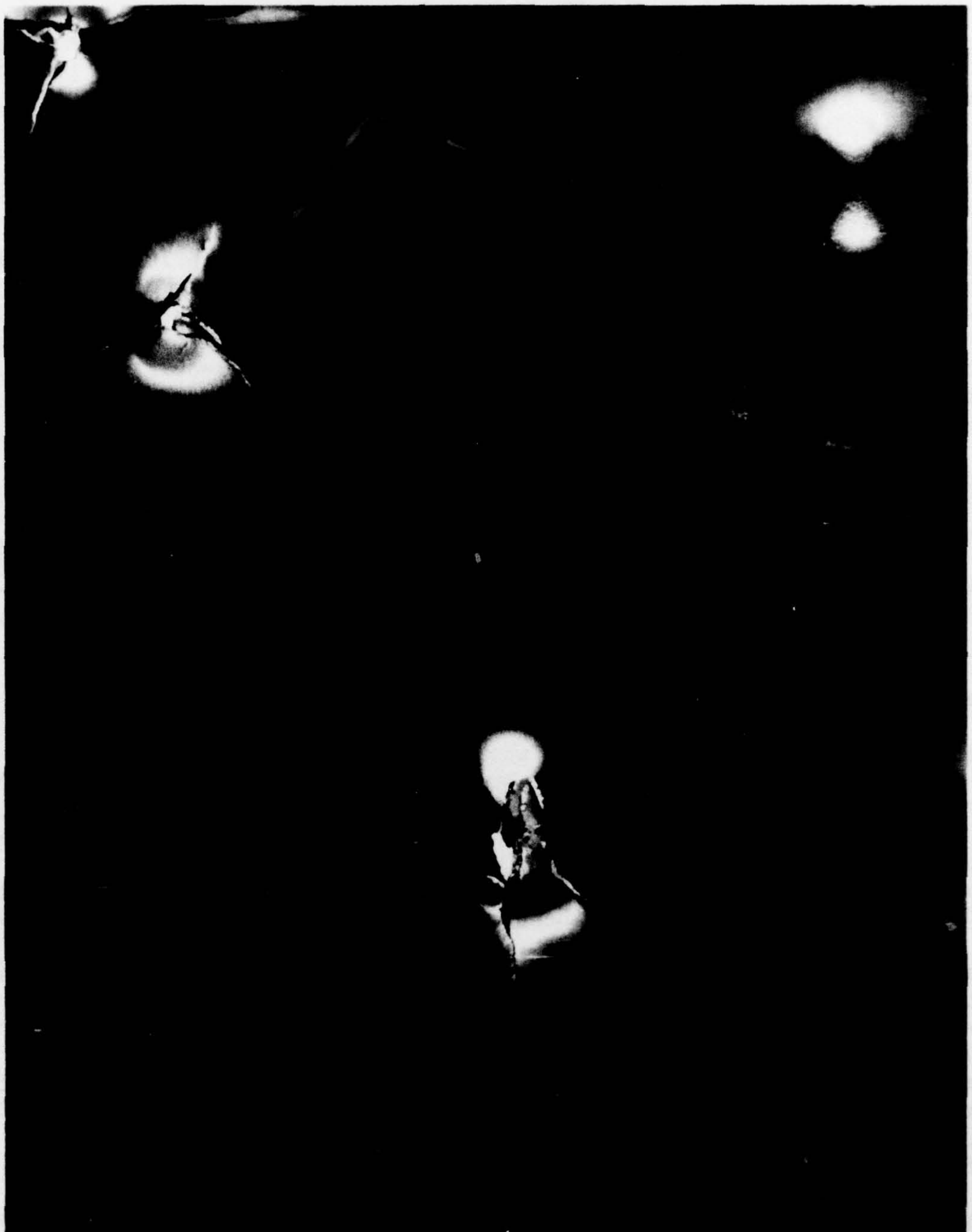

(b)

Figure 12. Front (a) and rear (b) faces of 0.25-inch resin-bonded octuple laminate of 7475-T371 0.032-inch sheet used to establish V_{50} for the 17.0-grain fragment-simulating projectile at 0° and 60° obliquities.

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and prevalent in the octuple laminate. Whereas laminate penetration was characterized by pronounced laminae deformation and tearing, ballistic limits did not correlate with petal formation. Thus, although the octuple laminate (which petaled profusely) performed best against the 17.0-grain FSP, the double laminate proved best against the 5.85-grain FSP.

Since tearing and petalling did not determine penetration resistance, it remains that increased deformation accounts for superior energy absorption of the laminates. The double laminate displayed less local deformation than did the quadruple and octuple laminates, but more bending of the 12 inch × 12 inch test plate under repeated impacts. Extensive delamination (adhesive failure) occurred in testing the double laminate (despite supplementary edge clamping of the test plate), whereas in the quadruple and octuple laminates delamination was confined to the vicinity of penetration. It should be recognized that delamination (adhesive failure) is in itself a mechanism for absorbing energy; moreover, once it has occurred, the debonded laminae are free to deform individually and further resist penetration.

Although the "solid" resin-bonded laminates showed superior resistance to penetration, it appears that they suffered more damage to themselves than did the single lamina (0.246-inch sheet) from equivalent fragment impacts. However, "damage" must be compared on the basis of (1) retained structural properties and (2) resistance to damage propagation (with accompanying loss of structural properties) during subsequent operation. These matters are beyond the scope of this report.

Spaced Laminates

Ballistic data for laminate designs wherein the sheets were separated (by edge spacers) shows they were inferior to solid 0.246-inch plate against the 5.85-grain FSP striking at 0° and 45° obliquities (see Figure 13). At 60° obliquity, however, the spaced laminate BLs were equivalent and the quadruple laminate were superior. Against the 17.0-grain FSP, the spaced double laminate was somewhat better than the plate at 0° and 60° obliquities. In general, the spaced laminates displayed lower BL than "solid" resin-bonded laminates of the same areal density.

Three triple laminate designs were tested to determine the effect of combining two thicknesses of sheet in various sequences on terminal ballistics at 60° obliquity. The three designs presented sheet thickness combinations of 0.062 - 0.062 - 0.125 inch, 0.062 - 0.125 - 0.062 inch, and 0.125 - 0.062 - 0.062 inch with respect to the impacting 5.85-grain FSP; sheet were spaced 0.125 inch apart in all three designs. The first and third design displayed comparable BL considerably higher than the second (see Items 8, 9, 10, Table 2). No explanation is offered for this seemingly anomalous behavior.

Turning now to comparison of monolithic versus laminate damage, it may be seen, whereas FSPs impacting the solid plate at high velocity caused considerable ejection of fragments by cratering, plugging and/or back-spalling, lamination served to modify these actions. Against the 5.85-grain FSP, resin-bonded double, quadruple, and octuple laminates showed less cratering on the front face, the last displaying petal formation wherein most petals remained attached (compare view (a)

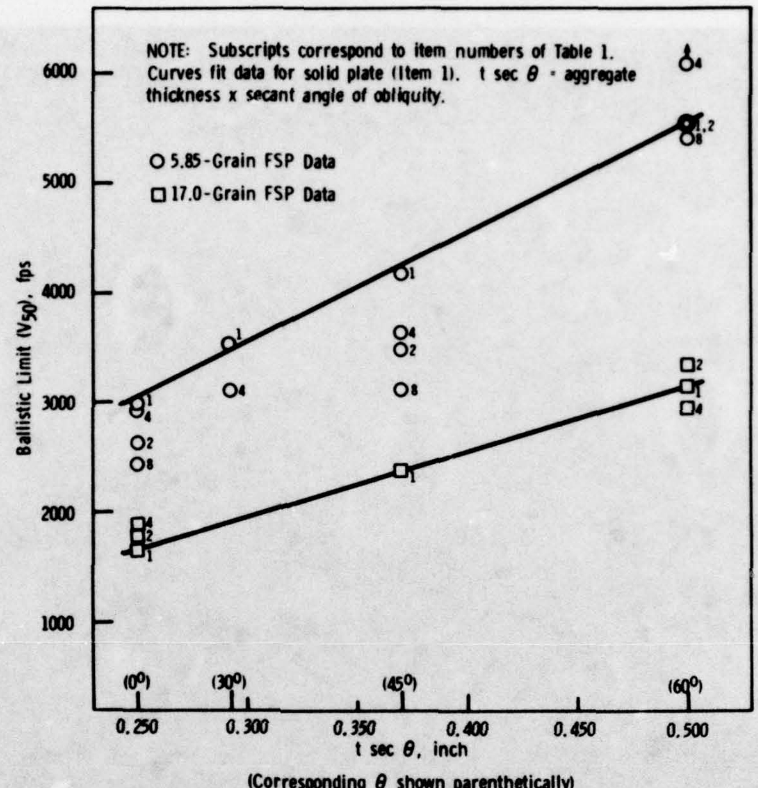
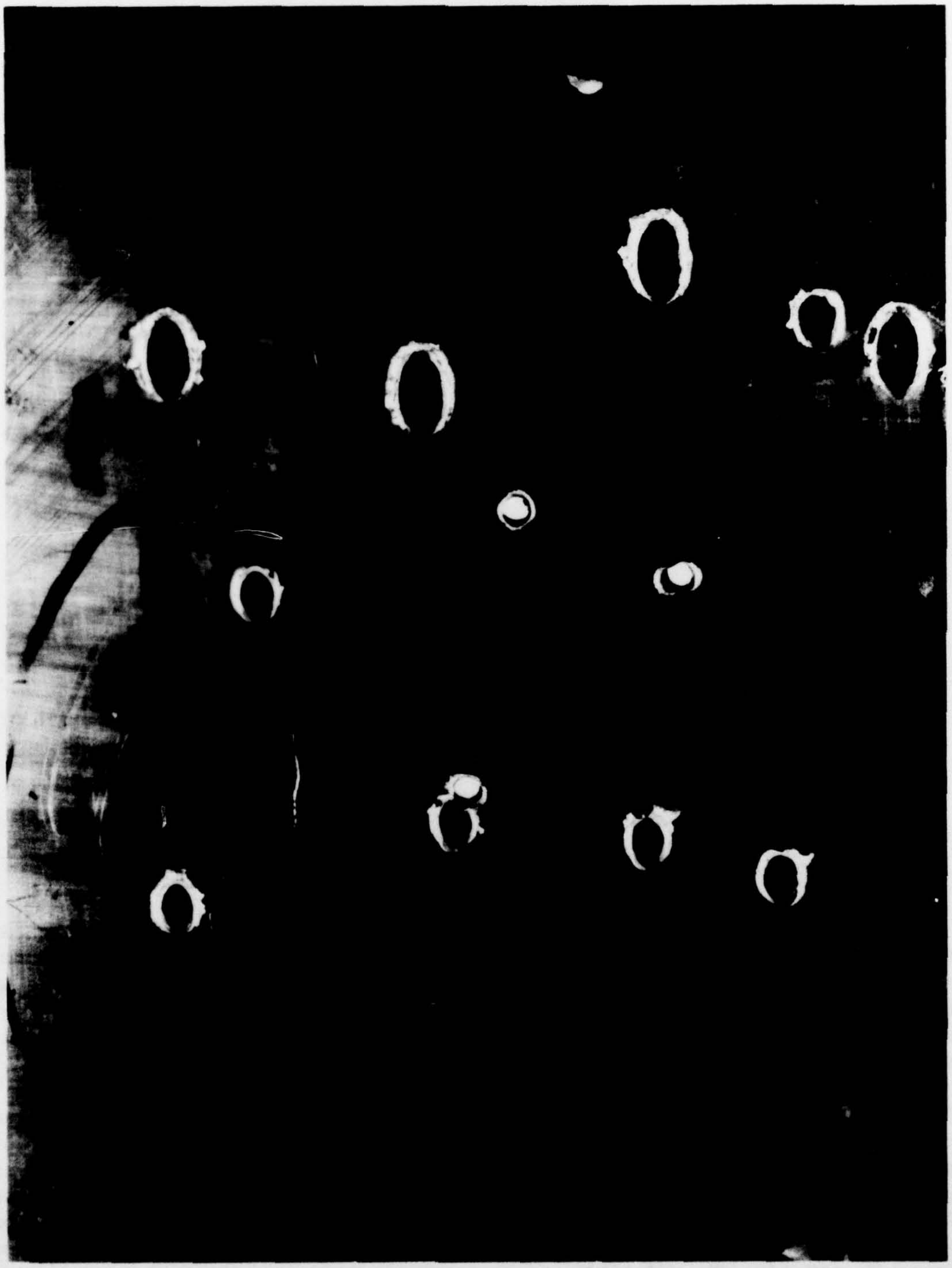


Figure 13. Ballistic limits (V_{50}) of 7475-T371 plate and spaced laminates of approximately 3.75 psf areal density at various obliquities versus 5.85- and 17-grain fragment-simulating projectiles.

in Figures 3, 7, 8, and 9). On the rear face these laminates showed no backspall; the double laminate showed plugging; the quadruple and octuple laminates displayed attached petals (compare view (b) in Figures 3, 7, 8, and 9).

Also against the 5.85-grain FSP, the double- and octuple-spaced laminates showed less cratering on the front face than did the solid 0.245-inch plate (compare view (a) in Figures 3, 14, and 15). Cratering was minimal on the octuple laminate. On the rear face the double-spaced laminate showed evidence of plugging only, whereas the octuple laminate showed plugging and incipient petalling (compare view (b) in Figures 3, 14, and 15).

Comparing metal loss from the front face of resin-bonded and spaced laminates on 5.85-grain FSP impact: loss from the double laminates appeared comparable (compare Figures 7a and 14a); loss from the spaced octuple laminate was less than that of the resin-bonded (compare Figures 8a and 15a). Comparing metal loss from the rear face: the double and octuple laminates appeared comparable, although petalling and damage size was much greater in the resin-bonded design (compare Figures 7b and 14b, 9b and 15b).



(a)

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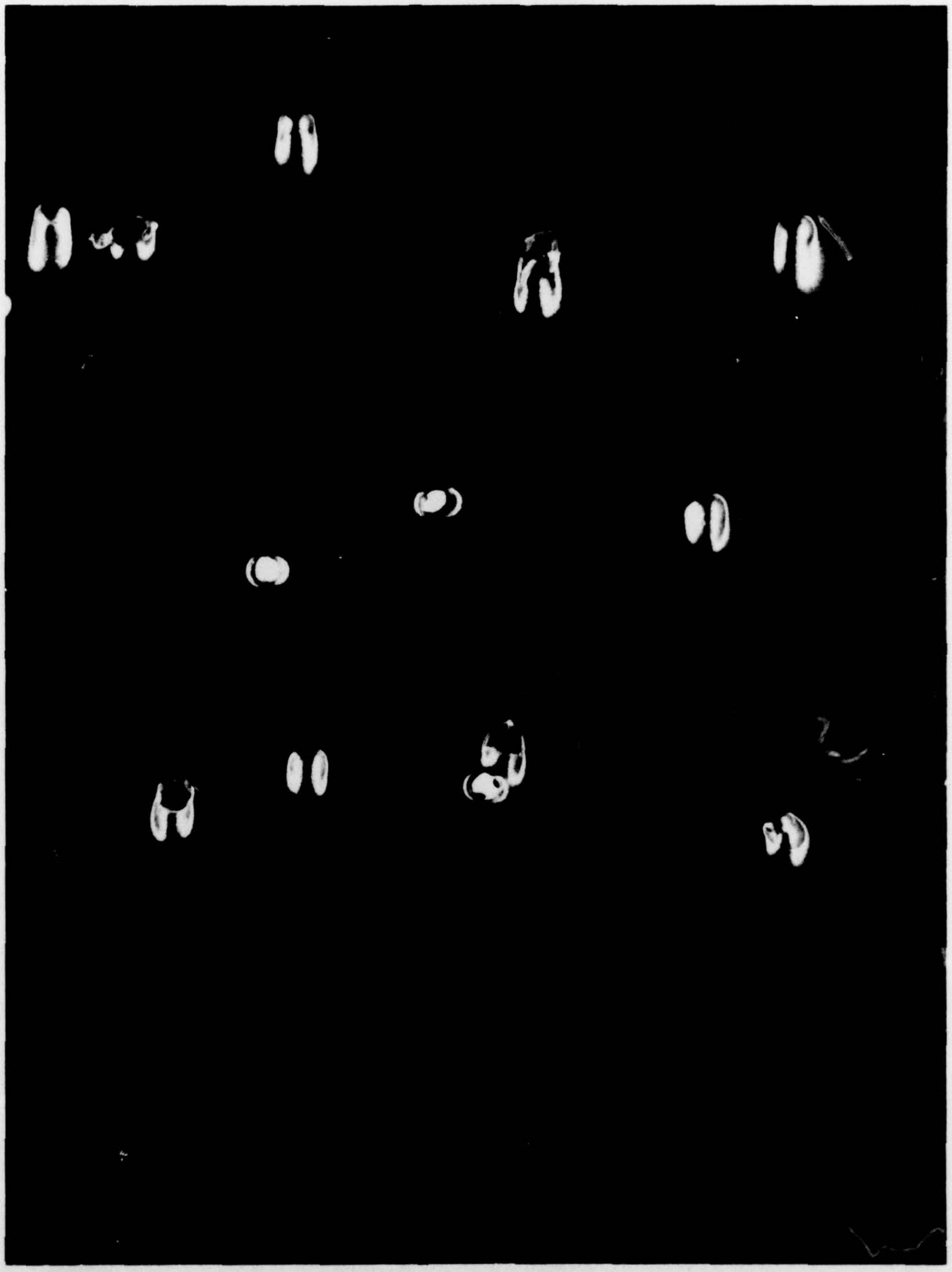

(b)

Figure 14. Front (a) and rear (b) faces of spaced double laminate of 7475-T371 0.125-inch sheet used to establish V_{50} for the 5.85-grain fragment-simulating projectile at 0°, 45°, and 60° obliquities.

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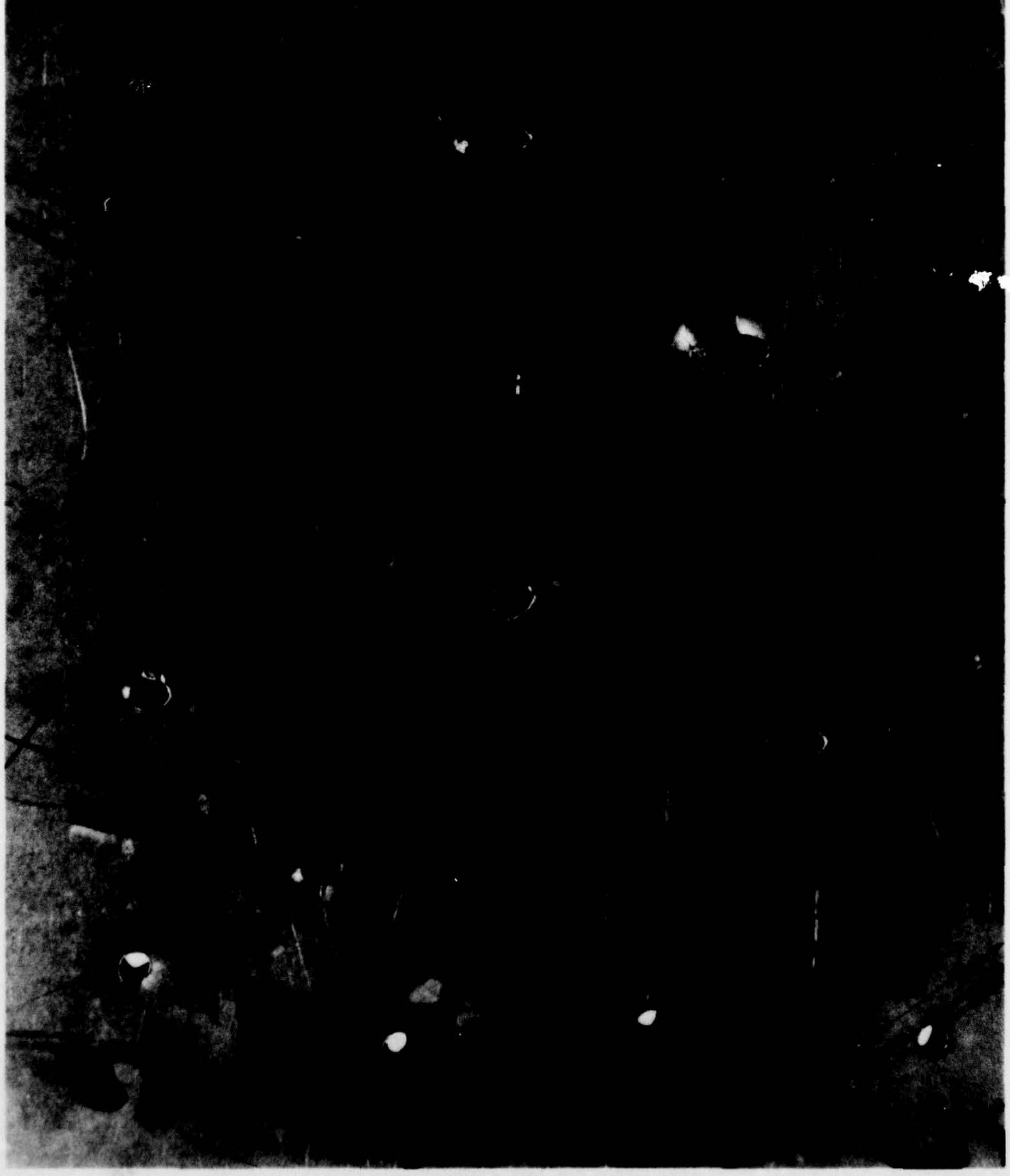

(a)

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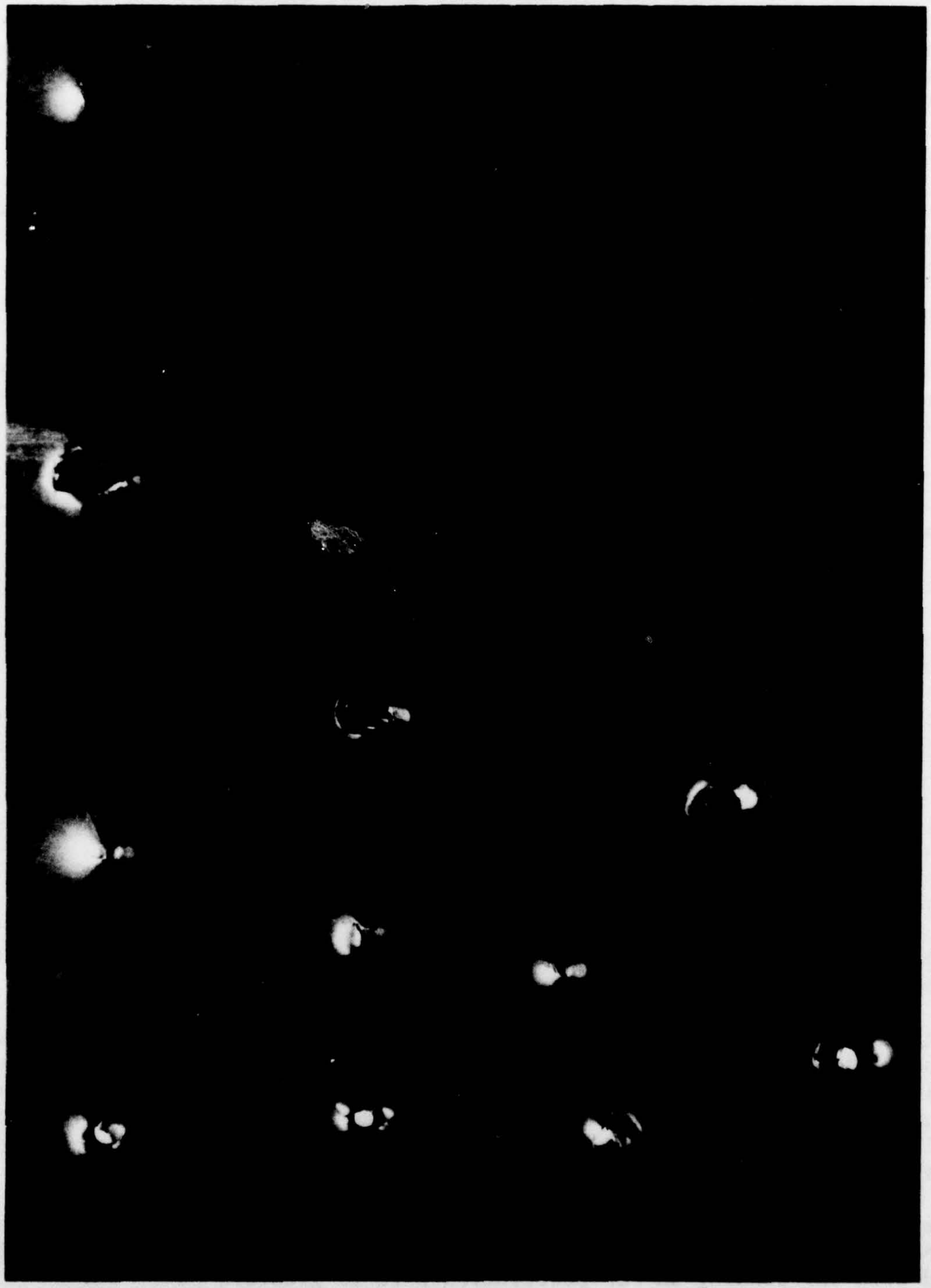

(b)

Figure 15. Front (a) and rear (b) faces of spaced octuple laminate of 7475-T371 0.032-inch sheet used to establish V_{50} for the 5.85-grain fragment-simulating projectile at 0°, 45°, and 60° obliquities.

19-066-957/AMC-76

Against the 17.0-grain FSP, resin-bonded double, quadruple, and octuple laminates showed progressively less cratering on the front face than did the solid 0.246-inch plate, the octuple laminate displaying large petals, mostly attached (compare Figures 4a and 10a, 11a and 12a). On the back face, the double laminate showed loss only from plugging, whereas petalling and damage size increased with lamination in the quadruple and octuple designs (compare Figures 4b and 10b, 11b and 12b).

Triple-spaced laminates (Items 8, 9, 10, Table 2), impacted by 5.85-grain FSPs, showed front and back face features corresponding to face and back sheet thickness (similar to those in Figures 14 and 15).

Aircraft Vulnerability Considerations

These visual comparisons show that lamination served to reduce the amount of metal ejected from the front face and eliminated spall from the back face when the target was impacted by FSPs. Resin-bonded laminates of thinner sheet showed back-face petal formation on penetration, the amount of sheet deformation, length of tears and size of petals increasing as sheet thickness decreased. Small petals formed on the front face of resin-bonded 0.032-inch sheet laminates. Sheet metal loss from the back face of target laminates resulted from plugging and/or detachment of petals occurring on complete penetration by the FSP. Spaced-laminate back-face loss was primarily by plugging. Resin-bonded laminates showed greater areas of deformation surrounding each penetration with correspondingly longer ruptures and larger petals; back-face loss in these laminates was from plugging and occasional petal detachment. Whereas damage potential of ejected target metal has not been assessed, it is suggested that heavier particles present some danger to personnel and soft components such as electronic devices. Accordingly, if spall and plugs from fragment penetration are to be avoided, these experiments indicate the following:

(1) Lamination tends to eliminate spalling (which was observed at FSP impact sites on the 0.246-inch plate).

(2) Plug weight is a function of sheet thickness.

(3) Spaced laminates of thinner sheet minimize front-face cratering and trap some sheet fragments internally, thereby reducing ejecta from the rear face.

Although spaced laminates offer some advantage in reducing ejection of target metal (particles of which could cause secondary damage), those spaced laminates tested in these experiments possessed BL ranging from considerably inferior to about equivalent those of solid 0.246-inch plate of the same areal density. Since spaced laminate structures would present a variety of fabrication and joining problems, added cost would also deter their application.

Whereas resin-bonded laminates have been shown to possess BL much superior to those of solid 0.246-inch plate of the same areal density, it seems that the affected area surrounding an FSP penetration site is greater, particularly for oblique impact. Commonly, laminae deformation and tearing occurs. If tears are considered criteria for establishing defect size, damage to the resin-bonded

laminates is more severe than that imparted by plugging through a solid plate. Whether residual service life of a structure fabricated of resin-bonded laminates would be correspondingly less cannot be inferred, however. Resin-bonded laminates tend to delaminate in the vicinity of FSP penetration. This tendency has not been assessed quantitatively, neither as a function of laminate design nor of various ballistic factors. It is to be expected that delamination would lower residual strength of the laminates in buckling and shear.

Resin-bonded sheet laminates offer (1) improved ballistic protection against HE shell/missile fragments, (2) reduced ejection of target metal with correspondingly less secondary damage, and (3) the possibility (as yet unconfirmed) for slower damage propagation during continued operation. The cost of military application would likely be greater than for monolithic materials presently in use. However, technology for producing such laminates is already in hand. Moreover, fabrication and assembly of resin-bonded sheet laminate structures does not apear to present formidable problems.[6] For these reasons, further evaluation of these promising materials is in order.

SUMMARY OF RESULTS

1. Tensile properties of 0.246-inch-thick 7475-T371 aluminum alloy plate and of resin-bonded sheet laminates of this same alloy that were designed to equivalent areal density possessed tensile properties ranging as follows: 68.4 to 76.5 ksi UTS, 61.9 to 69.8 ksi YS (0.2% offset), and 13.8 to 17.5 percent elongation. Directionality, either of the plate or of the laminates, was not appreciable.

2. Ballistic limits of 0.246-inch 7475-T371 plate against 5.85- and 17.0-grain fragment-simulating projectiles compare favorably on an areal density basis with those of 2024-T4 aluminum alloy plate.

3. The 5.85-grain FSP completely penetrated the 0.246-inch 7475-T371 plate at velocities ranging from 5571 fps at 60° obliquity to 2998 fps at 0° obliquity. (A representative 23-mm HEI shell fragment of this weight would likely achieve a velocity within the 4000 to 5500 fps range.) The 17.0-grain FSP penetrated this same plate at velocities ranging from 3158 fps at 60° obliquity to 1631 fps at 0° obliquity. (A representative 23-mm HEI shell fragment of this weight would likely achieve a velocity within the 3000 to 3200 fps range.)

4. "Solid" resin-bonded laminates of 7475-T371 sheet approximately equivalent in areal density to the 0.246-inch plate showed ballistic limits (V_{50}) as much as 10% higher than those of the plate against the 5.85-grain FSP and as much as 35% higher against the 17.0-grain FSP, depending upon obliquity and laminate design.

5. Spaced laminates of 7475-T371 sheet approximately equivalent in areal density to the 0.246-inch plate showed ballistic limits (V_{50}) which occasionally were better than those of the plate, depending again upon obliquity and laminate design, but which were generally inferior to those of the "solid" resin-bonded laminates.

6. ELLIS, J. R., and KUHN, G. E. *Adhesively Bonded Multilayer F-104 Aft Fuselage Ring Fitting.* AFML-TR-74-158 and AFFDL-TR-74-105, 1974.

6. Lamination served to reduce the amount of metal ejected from the front face and eliminated spall from the back face when the target was impacted by 5.85-grain and 17.0-grain fragment-simulating projectiles.

7. These findings indicate that laminated aluminum airframes would offer (a) increased resistance to penetration by fragments from shell such as the 23-mm HEI, (b) reduced damage by secondary fragments from the airframe itself, and (c) realization of the foregoing advantages without significant weight penalty. These findings were determined using aluminum alloy laminates; however, laminates of other structural alloys (such as titanium) may give similar benefits.

ACKNOWLEDGMENT

Tests involving use of fragment-simulating projectiles to velocities exceeding 6000 fps require special skill and precise control in order to obtain good data. Personnel of the Ballistic Test Range consistently met these needs. In particular, the author wishes to express his gratitude to Messrs. Salvatore Favuzza and Anthony DiCologero for their cooperation and assistance in conduct of this research.

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BALLISTIC BEHAVIOR OF ALUMINUM ALLOY
LAMINATES - Stuart V. Arnold

Technical Report AMMRC TR 77-24, October 1977, 35 pp -
illus- tables, D/A Project 1T162105AH84,
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